Francisco Manuel Parracho Lourenço

Licenciado em Engenharia e Gestão Industrial

A social life cycle assessment methodology for additive manufacturing products

Dissertação para obtenção do Grau de Mestre em Engenharia e Gestão Industrial

Orientador: Professora Doutora Helena Maria Lourenço Carvalho Remígio, Professora Auxiliar, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa

Júri:

Presidente: Prof. Doutora Maria Celeste Rodrigues Jacinto
Arguente: Prof. Doutora Inês Esteves Ribeiro
Vogal: Prof. Doutora Helena Maria Lourenço Carvalho Remígio

FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

março de 2018

LOMBADA

A social life cycle assessment methodology for additive manufacturing products

Francisco Lourenço

2018

A social life cycle assessment methodology for additive manufacturing products

Acknowledgments

The development of this dissertation would not be possible without the contribution and collaboration of several people. In this section, a sincere and special thanks are given to all these people for their support during these last months and throughout my academic course.

In the first place, I would like to thank my professor Helena Maria Lourenço Carvalho Remígio, for accepting me to be part of this project, and for all the patience, guidance, sharing of knowledge and constant availability demonstrated during the period of this research. I would also like to thank the PhD student Bardia Naghshineh, who was also part of this research project, for the support and advice given for the writing of this dissertation and for his openness to discuss specific subjects of this research.

Secondly, I would like to thank my friends who have been with me during this period and who have been part of my life since I remember my existence. To all of them, a huge thanks, for all the companionship and moments of fun, and for being with me in the good and bad moments of my life. I also want to thank all my colleagues whom I have met through these years of college, for all the memorable moments, for all the works and lessons we shared.

Finally, I want to thank my parents and my brother for giving me the opportunity to study, for their relentless support and for motivating me when I needed the most. They gave me the education, the values and the strength to overcome the obstacles that have appeared throughout my life, and that have made me the man that I am today.

The author gratefully acknowledges the funding of Project POCI-01-0145-FEDER-016414, co-financed by Programa Operacional Competitividade e Internacionalização and Programa Operacional Regional de Lisboa, through Fundo Europeu de Desenvolvimento Regional (FEDER) and by National Funds through FCT - Fundação para a Ciência e Tecnologia.

Resumo

A tecnologia aditiva, também conhecida como impressão em 3D, está a ganhar popularidade entre o público em geral, os media e as indústrias. É vista como uma tecnologia disruptiva com o potencial de substituir muitos processos de fabrico e de mudar a sociedade como a conhecemos. Com a sua rápida proliferação nos últimos anos, a compreensão dos possíveis impactos desta tecnologia sobre os *stakeholders* tornou-se um assunto crucial. Existem muitos estudos disponíveis na literatura em relação aos impactos económicos e ambientais da tecnologia aditiva. No entanto, a existência de estudos relativos aos impactos sociais desta tecnologia é ainda escassa. Por esse motivo, o principal objetivo desta dissertação foi desenvolver uma metodologia baseada na análise social do ciclo de vida para medir os impactos sociais de um produto feito por tecnologia aditiva, considerando diferentes *stakeholders*, e ao longo de diferentes fases do ciclo de vida. Para desenvolver a metodologia, foram adotadas seis etapas da metodologia análise social do ciclo de vida, nomeadamente: (1) Definição dos objetivos e do âmbito; (2) Seleção de categorias de *stakeholder*, subcategorias e indicadores para a tecnologia aditiva; (3) Definição de grupos de indicadores; (4) Método de cálculo e sistema de pontuação; (5) Desenvolvimento de um método para agregar as pontuações dos indicadores e (6) Interpretação dos resultados.

O segundo objetivo desta dissertação foi identificar possíveis indicadores que pudessem ser usados na metodologia proposta para medir os impactos sociais de um produto produzido por tecnologia aditiva. Um conjunto de 26 indicadores foi selecionado através da revisão da literatura. O terceiro, e último objetivo, foi validar os 26 indicadores selecionados, por forma a perceber se estes indicadores realmente capturavam os impactos sociais da tecnologia aditiva. Para esse propósito, foi realizado um estudo de caso exploratório numa empresa de tecnologia aditiva baseada em Inglaterra. Com base nos resultados, 20 dos 26 indicadores foram validados e podem ser usados na metodologia proposta.

Este estudo é o primeiro a propor uma metodologia baseada na análise social do ciclo de vida para medir os impactos sociais de um produto produzido por tecnologia aditiva. A metodologia proposta permite obter uma pontuação final que quantifica o impacto social do produto ao longo de todo o seu ciclo de vida. A metodologia também fornece pontuações para cada subcategoria, categoria de *stakeholder* e fase do ciclo de vida, o que facilita a identificação de pontos críticos que exigem a atenção das organizações envolvidas na cadeia de valor do produto. Para apoiar a implementação da metodologia proposta, foi também desenvolvido um modelo de aplicação computacional.

Palavras-chave: Tecnologia aditiva, Impactos sociais, Análise social do ciclo de vida, Metodologia, Indicadores

Abstract

The additive manufacturing technology, also known as 3D printing, is gaining popularity among the general public, the media, and in the industries. This technology is being viewed as a disruptive technology with the potential to replace many manufacturing processes and to change society as we know it. With its rapid proliferation in recent years, an understanding of the possible impacts of this technology on the stakeholders has become a crucial matter. There are many studies available in the literature concerning its economic and environmental impacts. However, research regarding the social impacts of this technology is still scarce. The main goal of this dissertation was to develop a methodology based on social life cycle assessment to measure the social impacts of an additive manufacturing product, on different stakeholders, throughout its different life cycle stages. In order to develop the methodology, six steps were adapted from the generally accepted social life cycle assessment methodology, namely: (1) Goal and scope definition; (2) Selection of stakeholder categories, subcategories and indicators for the additive manufacturing technology; (3) Definition of indicators groups; (4) Calculation method and scoring system; (5) Development of a method to aggregate the scores of the indicators and (6) Interpretation of the results.

The second objective of this dissertation was to identify possible indicators that could be used in the proposed methodology to measure the social impacts of an additive manufacturing product. A list of 26 indicators has been selected from the literature. The third and last objective was to validate the 26 selected indicators, to understand if these indicators really capture the social impacts of the additive manufacturing technology. To that end, an exploratory case study was conducted in an additive manufacturing company based in England. Based on the results of the case study, 20 of the 26 indicators were validated and can be used in the proposed methodology to measure the social impacts.

This study is the first to propose a methodology based on the social life cycle assessment to measure the social impacts of an additive manufacturing product, from a life cycle perspective. The proposed methodology is capable of providing a final score that quantifies the social impact of the product throughout all its life cycle stages. It also provides scores for each subcategory, stakeholder category, and life cycle stage, which facilitates the identification of hotspots that require attention by the organizations engaged in the value chain of the product. To support the implementation of the proposed methodology, a computational application model was also developed for the present study.

Keywords: Additive manufacturing, Social impacts, Social life cycle assessment, Methodology, Indicators

Index

Figure Index

Table Index

Acronyms and symbols

AM – Additive Manufacturing

CAD – Computer-aided design

DALYs - Disability adjusted life years

E-LCA – Environmental Life Cycle Assessment

DALYs - Disability Adjusted Life Years

FU – Functional Unit

ILO – International Labour Organization

ISO – International Organization for Standardization

LCC – Life Cycle Costing

OECD - Organisation for Economic Cooperation and Development

PET - Polyethylene terephthalate

PRP – Performance Reference Point

SETAC – Society of Environmental Toxicology and Chemistry

SLCA – Social Life Cycle Assessment

SLM – Selective Laser Melting

UNEP – United Nations Environment Programme

$\mathrm{W_i}$ - Number of stakeholders interviewed who attributed the score i to the indicator

V_i - Score i attributed to the indicator by the stakeholders in the questionnaire

$(\mathrm{f})_{\mathrm{i}}$ - Subcategory i aggregated score

$(\mathrm{e})_{\mathrm{i}}$ - Indicator i normalized score used to assess the subcategory

$(\mathrm{h})_{\mathrm{i}}$ - Life cycle stage i aggregated score

$(\mathrm{g})_{\mathrm{i}}$ - Stakeholder category i aggregated score affected in the life cycle stage

Chapter 1: Introduction

In this chapter, an introduction to the dissertation is presented. The motivation, objectives, research methodology and structure of the study are included in this chapter.

1.1 Motivation

This dissertation was developed under the "FIBR3D - Additive Manufacturing-based Hybrid Process for Long or Continuous Fibre Reinforced Thermoplastic Matrix Composites" project and aims to give continuity to the research developed by Lúcio (2017) and Ribeiro (2017), in the study of Additive Manufacturing (AM) technology's social impacts.

The FIBR3D project focuses on the emergent technology of AM and its application in fibre reinforcement thermoplastics. The main goal of the project is to develop a hybrid manufacturing process that combines both additive and subtractive operations into a single platform using thermoplastic matrix composites reinforced with fibers. The main promoter of the project is INEGI - Institute of Science and Innovation in Mechanical Engineering and Industrial Engineering, in partnership with four other institutions: LAETA – Laboratório Associado de Energia, Transportes e Aeronáutica, I3N – Instituto de Nanoestruturas, Nanomodelação e Nano fabricação, Centro de Investigação ALGORITMI (Universidade do Minho) and UNIDEMI – Unidade de Investigação e Desenvolvimento em Engenharia Mecânica e Industrial (Universidade NOVA de Lisboa).

AM usually referred to as three-dimensional (3D) printing is gaining significant interest amongst the general public, the academic community, and the industries due to its ability to create complex geometric parts with customizable material properties (Gao et al., 2015). The term AM refers to the technology or additive process of depositing successive thin layers of material upon each other, producing a final 3D object (Attaran, 2017). Contrary to the subtractive manufacturing process that removes excess material from a raw shape to achieve the intended geometry, the AM processes fabricate parts directly from a 3D computer-aided design (CAD) file by adding materials layer upon layer (Khajavi, Partanen, & Holmström, 2014).

AM technology has experienced rapid proliferation in recent years due to its capability to produce complex parts using a wide variety of materials, that is not possible with the conventional methods of production (Gao et al., 2015). The applications of this technology are vast, and many are not explored yet. Its building capabilities show enormous potential to be used in several application areas such as automotive, aerospace, engineering, medicine, biological systems, and food supply chains (Gao et al., 2015).

Despite being an immature technology, AM has been identified as having a huge potential for sustainable manufacturing (Ford & Despeisse, 2016). Sustainable manufacturing is the capability to use the natural resources for manufacturing in a conscious way, by developing products that are capable of fulfilling economic, environmental and social objectives (Garetti & Taisch, 2012). The increasing environmental awareness in our society and stricter environmental legislation in recent years led to an awareness increase of manufacturing companies regarding the sustainability of their processes and products (Kafara, Süchting, Kemnitzer, Westermann, & Steinhilper, 2017). According to Huang et al. (2013) “AM is expected to become a key manufacturing technology in the sustainable society of the future”. Among the many potential sustainability benefits of this technology, Ford and Despeisse (2016) highlights three that stands out: (1) the generation of less waste during manufacturing; (2) it extends the product life cycle through techniques such as repair, remanufacture and refurbishment and (3) it simplifies value chains by contributing to shorter and simpler supply chains and more localized production.

However, AM has not been sufficiently investigated from a sustainability perspective, resulting in little information about its impacts and effects on the environment, economy, and society (Nagarajan & Haapala, 2018). The majority of the studies found in the literature have focused on the energy consumption and environmental impacts of AM, with research assessing either the environmental performance of different types of AM or comparing AM with other conventional manufacturing processes. However, very few studies were conducted regarding the understanding and assessment of the AM social impacts. This lack of knowledge leaves a research gap in the body of literature. This dissertation aims to fulfill this gap by developing a methodology to assess the social impacts of an AM product.

As reported by The Interorganizational Committee on Guidelines and Principles for Social Impact Assessment (1994) social impacts are “the consequences on human populations of any public or private actions that alter the ways in which people live, work, play, relate to one another, organise themselves so as to meet their needs and generally cope as members of society”. The United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) Life cycle initiative (UNEP/SETAC, 2009) identified the social impacts of a product as consequences of social interactions formed between the product's surrounding system and the stakeholders engaged in the product life cycle.

Even though there are several tools and methods in the literature to assess the social impacts of products, the most consensus method within the international community and the most used in case studies developed in this area of study is the Social Life Cycle Assessment (SLCA) methodology. SLCA is the only social assessment method that considers the social impacts of products from a life cycle perspective (Wang, Hsu, & Hu, 2016). There are some references when conducting a SLCA study. One of them being the “Guidelines for Social Life Cycle Assessment of Products” by the UNEP/SETAC (2009). These guidelines provide a guidance framework for the assessment of social and socio-economic impacts of the products life cycle. These guidelines are a reference for this dissertation since it provides solid ground to conduct a social life cycle assessment study.

The research carried out for this dissertation revealed that several studies of SLCA were conducted to evaluate the social impacts of products manufactured by conventional manufacturing. However, no study has been found in the literature that applied the SLCA in the study of the social impacts of AM products. Therefore, this dissertation presents the first attempt to use the SLCA methodology to evaluate the social impacts of AM products.

1.2 Objectives

The main goal of this dissertation is to develop a SLCA methodology to assess the social impacts of a product made by AM. In this way, it is intended to indirectly measure the social impacts of using AM technology in production processes. In order to do this, the present study focuses on the following objectives:

- Identify possible indicators and metrics to measure the AM social impacts;
- Validate the identified indicators. This is, to determine if the indicators really capture the social impacts of AM technology;
- Develop a computational application model to support the assessment of the AM social impacts.

The methodology developed in this study, on the other hand, is expected to be an input for the FIBR3D project, in the development of a life cycle based parametric model to assess the performance of AM processes with regard to the three dimensions of sustainable development: economic, environmental and social.

1.3 Research Methodology

In research, the two main types of approach typically used are the deductive and inductive approaches. According to Kovács and Spens (2005), these research approaches differ in three aspects: (1) its starting point; (2) its aim and (3) the point where the final conclusions are drawn. In a deductive approach, researchers intend to develop propositions or hypothesis from existing theories (Dubois & Gadde, 2002). It follows a direction from a general law to a specific case. The deductive research starts with the examination of the existing theory through literature review, to then provide logical conclusions in the form of propositions or hypothesis that will be further tested and examined (Kovács & Spens, 2005). The inductive approach aims at generalizing findings from empirical data (Kovács & Spens, 2005). It consists of drawing generally applicable conclusions from the observation of a limited number of cases

(Alhamed & Qiu, 2007). Contrary to deductive research, the reasoning behind this approach follows a direction from a specific case to general law, i.e., from facts to theory (Kovács & Spens, 2005).

To achieve the objectives of this dissertation, both deductive and inductive approach will be used in the research process. First, the deductive approach will be used to identify and analyze existing methods in the SLCA literature that can be used to develop the proposed SLCA methodology. Based on the literature review, it is also intended to identify possible indicators that can be used to measure the social impacts of AM technology. In the end, the inductive approach will be used to validate the proposed indicators through an exploratory case study conducted in an AM company based in England.

1.4 Dissertation structure

This dissertation is structured into five chapters. The first chapter presents the motivation, the objectives and the research methodology of the study.

In the second chapter, the theoretical background considered relevant to the development of this study is presented. First, a literature review on the definition of AM technology and its social impacts is presented. Then, the SLCA methodology will be addressed, more specifically, its evolution, definition, framework, types of data and indicators and application challenges.

In the third chapter, a SLCA methodology is proposed to assess the social impacts of an AM product life cycle. The steps required to develop the proposed approach are explained in detail in each section of this chapter. In the end, a brief explanation of the computational application model developed to implement the proposed SLCA methodology is also provided.

The fourth chapter focuses on the application of an exploratory case study to validate the initial set of indicators used in the proposed SLCA methodology. First, the case study research methodology used is presented. Then, a description of the company and the data collection and analysis process is provided. In the end, the final set of indicators is proposed based on the results of the exploratory case study.

In the last chapter, the conclusions of the study are revealed, the main challenges and limitations encountered are identified, and recommendations are provided for future work.

Chapter 2: Literature Review

In this chapter, the literature considered relevant to the development of this study is presented. The first part will be designated for the characterization of the AM technology. It includes the identification of the types of AM processes, the materials used in AM and the advantages and main obstacles in its implementation. In the second part, the methodology used to develop the model proposed in this study, the SLCA will be described and analyzed. Its evolution, definition, framework and the main limitations on its implementation are topics that will be addressed. In the end, an overview of the SLCA case studies available in the literature is presented.

2.1 Additive Manufacturing

2.1.1 Additive Manufacturing characterization

AM has experienced tremendous growth in recent years. Due to its enormous potential, the use of this technology has been gaining importance in various fields of business and industries (Jiang, Kleer, & Piller, 2017). AM, also known as 3D printing, is a production process that consists of joining materials to make objects from 3D model data, usually layer upon layer (ASTM International, 2013). Contrary to the subtractive manufacturing, in which the products are fabricated by removing materials from larger stocks or sheets (for example, cutting, milling, stamping), AM builds parts by adding materials layer by layer (Huang et al., 2013). Khajavi et al. (2014) describe AM as a digital technology since it enables the production of physical objects from 3D CAD files. The AM production process can be described in the following steps (Li, Jia, Cheng, & Hu, 2017a):

1. A 3D CAD model of the object is generated, with all its details and dimensions;
2. The 3D CAD file is converted into a standard AM file format such as the traditional standard tessellation language (STL) format or the recent additive manufacturing file (AMF) format;
3. The STL or AMF file is sliced into tiny two-dimensional (2D) layers. Each slice of the STL or AMF file represents a 2D cross-section (layer) of the object to be produced;
4. These 2D layers are then sent to the 3D printing machine one layer at the time.

The 3D printing machine produces the object by printing each layer on top of the previous one, applying different solidification methods, depending on the raw materials in its production chamber (Kruth, Leu, & Nakagawa, 1998). The duration of the process can last for hours or days, depending on the dimension of the product and the required production precision (Khajavi et al., 2014).

AM can use materials such as plastics, resins, rubbers, ceramics, glass, metals and papers (Attaran, 2017). The input materials for these may come in the form of powders, filaments, liquids or sheets (Li, Jia, Cheng, & Hu, 2017b). The way that these materials are utilized depends on the type of AM process being used.

There are several AM processes, that differ from each other, in relation to how they build and consolidate the layers (Huang et al., 2013). Some processes use lasers or electric beams to melt the metal or powder together. While other processes use inkjet printing heads to spray binder or solvent into powdered ceramic or polymer. The most widely used AM processes are (Ford & Despeisse, 2016; Huang et al., 2013):

- Fused Deposition Modelling (FDM);
- Stereolithography (SLA);
- Selective Laser Sintering (SLS);
- Digital light processing (DLP)
- Electron Beam Melting (EBM);
- Laminated Object Manufacture (LOM);
- Laser Engineered Net Shaping (LENS);
- Three-Dimensional Printing (3DP);
- Inkjet Printing (IJP)

Another AM process that has gained relevance in recent years in the industrial manufacturing sector is the Wire - Arc Additive Manufacturing (WAAM) process (Wu et al., 2018). This process stands out from the other AM processes because it enables the production of large metal components (up to several meters), with high-efficiency deposition rates, fewer equipment costs and high material utilization (Montevecchi, Venturini, Scippa, & Campatelli, 2016; Wu et al., 2018).

AM was first introduced in the world in 1980 as a technique for producing physical prototypes of products, which, at the time, allowed significant time and cost reductions in the development phases of products (Ford & Despeisse, 2016). Since then, this technology has been evolving continuously in different aspects along with the development of information technology and the emergence of new materials (Li et al., 2017a). With this evolution, more and different parts are being produced by AM technology with the appropriate levels of precision and quality required to be used for specific applications, in different areas. The AM technology has been widely used in on-demand manufacturing, and in other industries such as aerospace, automotive, and machine tool production sectors, as well as in medical and dental care. In his work, Attaran (2017) highlights the main benefits gained from the use of this technology in these industries. More recently, home 3D printers began to be developed and commercialized for consumer use. With these 3D printers, consumers will be able to produce their own customized parts at their convenience (Ford & Despeisse, 2016).

Due to the characteristics and building capacities of AM, there are numerous advantages associated with this type of manufacturing. According to Huang et al. (2013) and comparing with the conventional manufacturing process, the main advantages are:

- **Material efficiency:** One of the main advantages is related to the waste reduction resulting from the product production. While in traditional manufacturing processes, large quantities of materials need to be removed to produce the final product, in AM technology the raw materials are used efficiently since the product is built by adding materials layer by layer. Furthermore, the leftovers materials in the AM processes can be reused with minimal processing.
- **Resource efficiency:** The AM technology does not require additional resources, like the ones used in conventional manufacturing processes, for example, fixtures, cutting tools, and coolants.
- **Part flexibility:** In AM, there are no tooling constraints, which allows that products with very complex geometric characteristics and shapes, can be produced in fewer parts, and even, in single pieces. Thus, it is not necessary to sacrifice the functionality of the part, for the simplification of the manufacturing or assembly processes.
- **Production flexibility:** The AM machines do not need setups, which is an excellent advantage for example, in the production of small batches. Since complex parts can be produced in single pieces, problems such as line balancing and production bottlenecks, often verified in traditional manufacturing processes, are also eliminated. Furthermore, in AM, the quality of the products depends exclusively on the performance of the processes, rather than the skills of the operators.

Despite its advantages, AM technology still cannot replace or compete with traditional manufacturing because of several limitations that represent major obstacles, for example, in mass production. According to Huang et al. (2013), these obstacles are:

- **Size restrictions:** The major constraint perhaps in AM is related to the fact that the 3D printers used in AM, can only produce objects that are smaller than the size of the printer. Another constraint is related to the main materials that are used to build the object layers, which is the case of liquid polymers and powders composed of resin or plaster. The lack of strength of these materials does not allow AM to produce large-sized objects. Also, very large objects would require a considerable amount of time to conclude the process.
- **Imperfections:** The appearance of an end part produced by AM is often characterized for having rough and ribbed surfaces finish. In AM, products are built by depositing layers upon layers. The boundaries of each layer can sometimes create saliences in the surface that confer an unfinished look to the end product.
- **Cost:** Another constraint is the effective cost of the equipments used in AM. Regardless of the type of the model of the machine (entry or high-end models), these equipments are considered expensive investments. However, with the development of technologies and the increase in the

number of entities that will enter this market, the price of the printers will certainly decrease in the next years.

AM technology is being viewed as a disruptive technology with the potential to replace many manufacturing processes in a nearing future (Zhou, Huang, & Liu, 2015). Several processes engaged in the value chain of a product, such as logistics, supply chain design, product planning, and consumer behavior will also be influenced by the AM technology. Moreover, new business models, new supply chains and new products will be created with the continuous use of this technology (Jiang et al., 2017).

2.1.2 Additive Manufacturing social impacts

As previously mentioned, AM is a disruptive technology that is changing the industry as we know it. Like the other disruptive technologies such as the internet, e-mail, smartphones, when they emerged, the impact that these technologies could have on people and society, in general, was unclear. With the increasing use of AM technology in recent years, several researchers have now focused their efforts on the study of the sustainability implications of this technology. The majority of these studies have been done on a broader level, referring to general aspects of the three dimensions of sustainability (Chen et al., 2015; Ford & Despeisse, 2016; Ma, Harstvedt, Dunaway, Bian, & Jaradat, 2018), or have been highly focused on the issue of material and energy consumption (Al-Meslemi, Anwer, & Mathieu, 2018; Kellens, Mertens, Paraskevas, Dewulf, & Duflou, 2017; Peng, Kellens, Tang, Chen, & Chen, 2018).

Nonetheless, academic studies focusing on the social impacts of this technology are even more limited. To date, the most detailed study on this topic is the review paper of Huang et al. (2013), in which the authors addressed the social impacts of this technology in several areas, namely on population health and well-being, energy consumption and environmental impact, manufacturing supply chains and potential health and occupational hazards. The same authors stated that AM has higher health benefits compared to traditional manufacturing processes, such as casting, forging, and machining since it allows workers to avoid long-term exposure to potentially hazardous work environments. However, due to little research on the topic, it is not clear which toxicological and environmental hazards that may be associated with the processing and disposing of the materials used in AM processes (Chen et al., 2015). Furthermore, positive impacts of the technology, includes the possibility of production of customized surgical implants and assistive devices in the healthcare industry, the efficiency regarding material and water consumption, less pollution and the simplification of the supply chains (Huang et al., 2013).

More recently, Ribeiro (2017) in his master thesis also addressed the social aspects of AM technology and identified 26 social impacts under 11 categories, namely educational perspective, commercial view, intellectual property, employment and labour structures, access to the technology, economic, environment and energy consumption, supply chain, health and occupational hazards, healthcare and safety and governmental approach. Table 2.1 presents the social impacts identified by the author, for each of the eleven categories mentioned above. Each social impact is discussed in greater detail in his work.

Table 2.1 - Additive Manufacturing social impacts

Adapted from Ribeiro (2017)

Categories	**Social Impacts**
Educational perspective	• Educate the workforce to the technology • Presence of the technology in the universities increased • People are self- taught
Commercial view	• Product life extension • Cost reduction • Foreign production reduction, domestic increase • Delay reduction
Intellectual property	• Legal battles increase • Legal structures are not at par with AM technology capabilities
Employment and labor structures	• Labor demand reduction • Qualified workforce demand increase • Creation of new jobs and industries
Access to the technology	• The technology is accessible to the majority of college students • Home 3D printers will produce the parts to suit the local community needs
Economic	• De-globalization of production and distribution • Countries reduce their exportation volume
Environment and energy consumption	• Less energy and material consumption • Less impact on the pollution of terrestrial, aquatic, and atmospheric systems
Supply chain	• Efficiency on a lean supply chain improved • Responsiveness of an agile supply chain improved
Health and occupational hazards	• Exposure to toxic substances increased • Gases with noxious environmental impacts are produced • Lead and nickel are produced
Healthcare and safety	• Surgical parts are produced to suit the patient needs • Personal protective equipment production
Governmental approach	• Production of weapons

2.2 Social Life Cycle Assessment

In this section, the theoretical background of the SLCA methodology is presented. The goal is to provide an overview of the methodology, focusing on its evolution, definition, concepts, steps, and limitations. Moreover, previous studies regarding the application of the methodology in different products and considered relevant to the present study, are also presented.

2.2.1 What is Social Life Cycle Assessment?

The SLCA can be considered as a life cycle assessment methodology that complements the Environmental Life Cycle Assessment (E-LCA) and the Life Cycle Costing (LCC) with the social and socio-economic aspects, contributing to the full assessment of goods within the context of sustainable development (UNEP/SETAC, 2009). It can either be applied on its own or in combination with both E-LCA and LCC methodologies. According to UNEP/SETAC (2009), SLCA is a " technique that aims to assess the social and socio-economic aspects of products and their potential positive or negative impacts along their life cycle." In SLCA, the life cycle of the product is addressed from a "cradle to grave" approach, which means that all life cycle stages of the product can be considered, from extraction to the disposal (Figure 2.1). These are usually related to resource extraction, manufacturing, distribution, use, disposal, remanufacturing and reuse, among others, depending on the product under assessment (UNEP/SETAC, 2009).

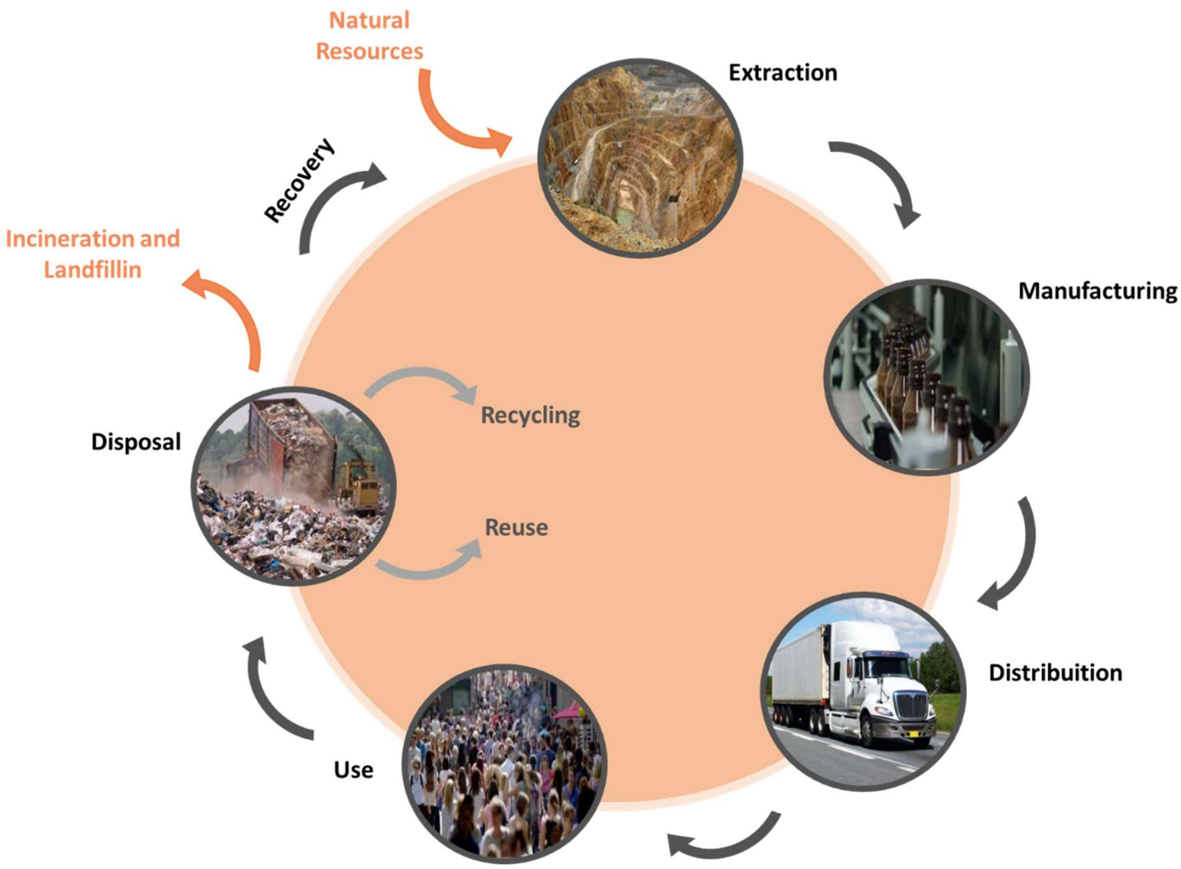


Figure 2.1 - Product Life cycle

Adapted from UNEP/SETAC (2009)

Despite in its definition SLCA is referred to as a "technique", other authors also refer to it as a method (Arcese, Lucchetti, Massa, & Valente, 2018; Lenzo, Traverso, Salomone, & Ioppolo, 2017), a methodology (Di Cesare, Silveri, Sala, & Petti, 2018; Sureau, Mazijn, Garrido, & Achten, 2017) or an approach (Singh & Gupta, 2017; Wang et al., 2016). In this research, SLCA is considered a methodology comprising a set of steps to measure the social impacts of products. It includes the specification of methods to collect data and techniques to manipulate data.

SLCA differs from other social impacts assessment techniques by its objects: products and services, and its scope: the entire life cycle (UNEP/SETAC, 2009). The social and socio-economic aspects assessed in this methodology are those that may directly affect the stakeholders during the life cycle of a product, in a positive or negative way, and are usually linked to the behaviors of enterprises, to socio-economic processes, or impacts on social capital. That is to say, that social impacts are connected with the production processes and other business practices that take place along the life cycle of a product, and can be responsible for major or minor impacts that can have either positive or negative effects on stakeholders (Tsalis, Avramidou, & Nikolaou, 2017; UNEP/SETAC, 2009).

According to Benoît et al. (2010), SLCA can be used to identify, study, communicate and report social impacts, to support the implementation of strategies or actions plans. This technique can also be used to support the organizations in the decision-making processes, such as supplier's selection, purchasing policies and management policies, by providing information on the social impacts of their products or services. The SLCA does not provide information on whether a product should be produced or not. Despite the information on the social conditions of production, use and disposal of the product may provide elements to incite discussion on this topic, in itself this tool does not have the capacity or the role of informing the decision makers at this level (UNEP/SETAC, 2009).

Thus, the ultimate goal for conducting an SLCA study is to promote the improvement of the social conditions of a product throughout its life cycle. Furthermore, it also aims to incite the dialogue between the decision makers on the importance of social and economic aspects of production and consumption, in the prospect to improve the organizations' performance and consequently, the well-being of its stakeholders (Bork, Junior, & Gomes, 2015; UNEP/SETAC, 2009).

2.2.2 Evolution of Social Life Cycle Assessment

The idea of including social aspects in the Life Cycle Assessment (LCA) methodology began three decades ago, with the publication of the SETAC Workshop Report: "A Conceptual Framework for Life Cycle Impact Assessment" in which the author proposed a new impact category, named "social welfare impact category" (Fava et al., 1993). O'Brien et al. (1996) published the first paper on this subject, in which the authors propose a methodology known as Social and Environmental Life Cycle Assessment (SELCA), that complements the E-LCA, by identifying social factors that contribute to environmental issues (Hosseinijou, Mansour, & Shirazi, 2014). Furthermore, O'Brien et al. (1996) also stated that the inclusion of social assessment could lead to a true sustainability assessment, including the three dimensions of sustainable development: social, economic and environmental. There was an increasing interest in the life cycle assessment community to include the social aspects in the ELCA (Gauthier, 2005; Jolliet et al., 2004; Klopffer, 2003; Udo de Haes, Jolliet, Norris, & Saur, 2002). Following this early body of research, investigators addressed their efforts on finding ways to assess social impacts separately from the ELCA, developing new approaches and frameworks that alone could assess the social aspects of products and services.

In 2004, UNEP became aware of the need for a task force on the integration of social criteria into LCA, and with the collaboration of SETAC, they started a project called the UNEP/SETAC Life Cycle Initiative. The working group was composed at the time by more than 70 experts in the subject and was created with the following purposes (UNEP/SETAC, 2009):

- The conversion of the current environmental tool LCA into a triple bottom line sustainable development tool;
- The establishment of a framework for the inclusion of socio-economic benefits into LCA;
- The determination of the implications for life cycle inventory analysis;
- The determination of the implications for life cycle impact assessment;

Following several meetings, workshops and seminars, the UNEP/SETAC working group met its objectives by publishing in 2009 the "Guidelines for Social Life Cycle Assessment of products" (UNEP/SETAC, 2009). These guidelines provide a guidance framework for stakeholders engaging in social impact assessment for products over their complete life cycle. To complement the guidelines and support the development of SLCA case studies, UNEP/SETAC (2009) also published "The Methodological Sheets for Subcategories in Social Life Cycle Assessment" (UNEP/SETAC, 2013) to clarify the concepts of subcategories and to recommend indicators and its data sources.

In addition to the UNEP/SETAC Guidelines, several other frameworks were developed in this field in the period from 2005 to 2016. Sureau et al. (2017) identified 14 SLCA methodological frameworks in their review work (Table 2.2). The authors classified the frameworks into five types, on the basis of the origin and selection of its assessment criteria and indicators:

- **Value base frameworks:** Use international agreements, but also consultations with stakeholders at an international level;
- **Context-oriented frameworks:** Defines assessment criteria also on the basis of values, but where these are specific to a context;
- **Theory-structured frameworks:** Uses theoretical models to structure and select criteria;
- **Impact-based framework:** It develops impact pathways between an impact and the origin of this impact. The assessment criteria is selected by backtracking from assumed or observed effects/impacts to social stressors;

Table 2.2 – Social Life Cycle Assessment frameworks classified according to its type, purpose, assessed phenomena and applicability

Adapted from Sureau et al. (2017)

Type of framework	**General Frameworks**	**What is the purpose?**	**What is assessed?**	**Applicability**		
				Meant to be Universal	**Adapted to sector**	**Adapted to local context**
Value-based framework -	Guidelines for SLCA (UNEP/SETAC, 2009)	Identify hotspots and improvement options; reduce risks; and establish purchasing procedures or specifications, marketing, reporting and labeling, strategic planning, public policies development	Social aspects of products and their potential positive and negative impacts along their life cycle	×		×
	Dreyer et al. (2006)	Support business decision-making	Conduct of company towards its stakeholders	×	×	
	Kruse et al. (2009)	Inform consumers' personal Socioeconomic impacts practices and policymakers' on relative socioeconomic costs of comparable products from different production systems	Social impacts linked with a production	×	×	×
Context-oriented framework	SLCA participatory approach (Mathe, 2014)	Support decision-making	Level of well-being generated by the ecosystem services provided by the industry			×
	Nussbaum capabilities S-LCA (Wangel, 2014)	Use SLCA results as design criteria in the process of constructing a new chain	Variation of the functioning of stakeholders through the value chain			
Theory-structured framework	Alkire capabilities SLCA (Reitinger et al., 2011)	Conduct comparative analysis at the level of sector/industry, for strategic analysis, complex decision-making processes, identify optimization potentials within an organization.	Degrees of freedom and functioning of stakeholders			×
	Falque et al. (2013)	Support to decision-making through the identification of consequences of a modification of the social condition	Effects and impacts of an activity on the transformation of dotation of additional functioning capabilities		×	

Table 2.2 – Social Life Cycle Assessment frameworks classified according to its type, purpose, assessed phenomena and applicability (cont.)

Adapted from Sureau et al. (2017)

Type of framework	**General Frameworks**	**What is the purpose?**	**What is assessed?**	**Applicability**		
				Meant to be Universal	**Adapted to sector**	**Adapted to local context**
Theory-structured framework	PROSUITE (Gaasbeek & Meijer, 2013)	Support decision-making for product developers, policymakers, and businesses	Effect of the introduction of a technology		×	
Impact-based frameworks	Impact pathway (Macombe eta al., 2013)	Support decision-making	Impacts of a change in the functioning of the life cycle of a product			×
Applicability-oriented frameworks	Labuschagne et al. (2007)	Business management purpose	Social sustainability of an operational initiative: effects of engineering projects or technologies in the process industry			
	AgBalance/SeeBalance (Schoeneboom et al., 2012)	Identify options for improvement and to communicate	Current practices and processes, impacts of regulations on products and farming practices at different levels	×		
	Product Social Metrics (Fontes, 2014)	Identify improvement potentials, highlight positive impacts, help decision-making and communicate	Positive and negative impacts of the product on workers, consumers, and local communities	×		
	Social Hotspot Database (SHDB) (Benoit-Norris et al., 2012)	Prioritize for where site-specific data collection is most desirable	Identification of hotspots, i.e., production activities or unit processes in the supply chain that may be at risk for social issues	×		
	PSILCA (Ciroth & Eisfeldt, 2016)	As for Social Hotspot Database (SHDB)	As for SHDB	×		

- **Applicability-oriented frameworks:** Most of these frameworks are based on the work done through the Guidelines. The selection of the criteria is made through consultation with experts. The resulting list of criteria is generally meant to apply to any context.

In their work, Sureau et al. (2017) also classified each framework according to its purpose, assessment phenomena and context of applicability, as shown in Table 2.2. They concluded that most of the addressed frameworks used the UNEP/SETAC Guidelines as a basis for selecting its assessment criteria and indicators. The purpose of the majority of the frameworks addressed was identified as being the support in decision making and the identification of areas of improvement. On the other hand, the assessed phenomena in the frameworks were not only the social aspects of products but also company practices, the level of well-being generated by an industry or the variation in capabilities of stakeholders.

Despite the vast number of SLCA methodological frameworks existing in the literature, the UNEP/SETAC Guidelines continue to be the main reference among the SLCA research community to study the social impacts of products. The publication of the guidelines (UNEP/SETAC, 2009) and its complementary methodological sheets (UNEP/SETAC, 2013) was considered a cornerstone in SLCA development, giving practical guidance on how to conduct social life cycle assessment. As a result, following their publication, the number of case studies applying the methodology in different products has exponentially increased (Petti, Serreli, & Di Cesare, 2016). Nowadays, the guidelines are still being applied in several case studies and different international projects, contributing to the improvement of the methodology (Lúcio, 2017).

2.2.3 Social Life Cycle Assessment methodology according to the UNEP/SETAC Guidelines

The general methodology for SLCA implementation relies on the UNEP/SETAC Guidelines for Social Life Cycle Assessment (UNEP/SETAC, 2009), which follows the structure suggested by ISO 14040 and 14044 for ELCA. Figure 2.2 illustrates the assessment framework suggested in the UNEP/SETAC guidelines. The SLCA methodology comprehends four main phases:

1. **Goal and scope definition:** The first phase aims to identify the reasons for conducting the study and to define its depth and breadth (UNEP/SETAC, 2009). In the scope definition, the limits are defined on the product's life cycle. This phase of the study also includes the description of the functional unit, the product system, system boundaries, the data type to be collected, the selection of stakeholders, subcategories, and indicators, the impact assessment method, and the assumptions and limitations of the study.
2. **Inventory analysis:** The objective of the inventory is to collect relevant data, identified during the scope definition (Jørgensen, Le Bocq, Nazarkina, & Hauschild, 2008). Data collection can be the most time-consuming step in SLCA. Whenever possible, the data used in SLCA should

be site-specific, i.e., collected from the organizations involved in the life cycle stages of the product. However, generic data related to the localities/regions/countries where the organizations are settled can also be considered in SLCA.

3. **Impact assessment:** The third phase of SLCA methodology involves the linkage of the inventory data to the respective subcategories and impact categories (classification) and the determination or calculation of the subcategories indicator results (characterization) (Foolmaun & Ramjeeawon, 2013). According to the UNEP/SETAC guidelines, two characterization models can be used to aggregate the inventory to impact categories: type I and type II. The type I model does not incorporate causal relationships, and the indicators results are calculated and aggregated for the subcategories, through a scoring system and/or a weighting system (Wu, Yang, & Chen, 2014). In the type II model, the inventory indicators are linked with midpoint and endpoint impact categories, through impact pathways, i.e., casual relationships (Wu et al., 2014).
4. **Interpretation:** The objective of the last phase of SLCA is to assess and analyze the results of the impact assessment to identify important issues such as key concerns, limitations, and assumptions made during the study (UNEP/SETAC, 2009). In the end, the conclusions are drawn in relation to the defined goal and scope.

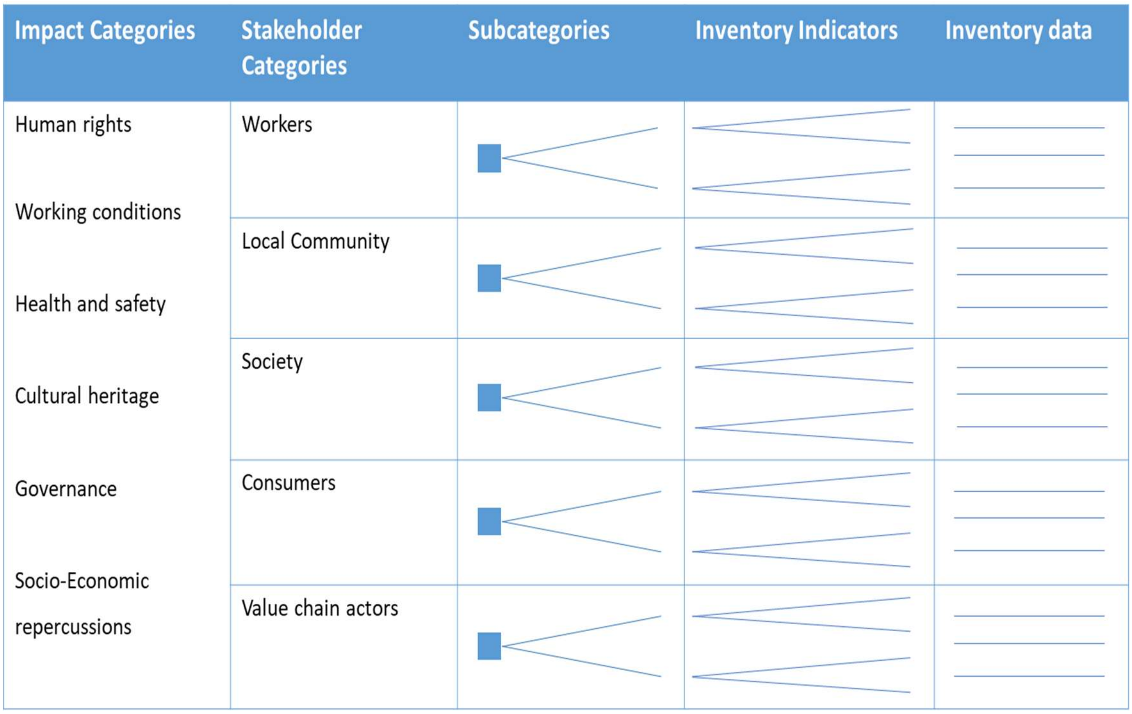


Figure 2.2 - Assessment framework in Social Life Cycle Assessment

Adapted from UNEP/SETAC (2009)

The SLCA methodology assesses the social impacts of a product from a life cycle perspective, by looking at the complete life cycle of a product, from extraction to disposal (UNEP/SETAC, 2009). Each stage of the product life cycle can often be associated with different geographic locations, since the organizations that are involved in the value chain of the product may operate in different countries or regions (Benoît et al., 2010). According to UNEP/SETAC (2009), at each one of these geographic locations, the social impacts can be observed in five main stakeholder categories:

- **Workers -** Employees working in the various areas of the product's supply chain;
- **Local communities -** People or groups of people who live and/or work near the site of the company's facilities;
- **Society –** National and global;
- **Consumers -** Covering not only the end-consumers but also the consumers that are part of each section of the supply chain;
- **Value chain actors -** All manufacturers and/or importers and/or downstream users in a supply chain, not including the consumers.

Stakeholders categories are clusters of stakeholders that are expected to have shared interests due to their connection to the product under assessment. The stakeholder categories just outlined are considered the main categories potentially impacting on the life cycle of the product.

Each stakeholder category is associated with a number of subcategories, which are socially significant themes or attributes such as child labor, fair salary, health and safety, local employment, corruption, among others. Not only does the classification of social impacts into stakeholder categories and subcategories aim to identify and categorize the ways in which the stakeholders can be affected by the product life cycle, but it also supports further impact assessment and interpretation (UNEP/SETAC, 2009).

Table 2.3 shows the 30 subcategories suggested in the UNEP/SETAC guidelines (UNEP/SETAC, 2009) distributed by the five main stakeholder categories. All the subcategories proposed in the guidelines are explained and detailed in the document complementing the guidelines, "The Methodological Sheets for Subcategories in the Assessment of the Social Life Cycle Assessment" (UNEP/SETAC, 2013).

The subcategories are classified according to stakeholder groups and impact categories and are evaluated using inventory indicators (Figure 2.2). Several indicators may be used to assess each of the subcategories. Each inventory indicator specifically defines the data to be collected. Thus, indicators can be quantitative, semi-quantitative or qualitative depending on the type of data used to measure them (Benoît et al., 2010).

Table 2.3 - The stakeholder categories and subcategories proposed in the UNEP/SETAC Guidelines

Adapted from UNEP/SETAC (2009)

Stakeholder Categories	Subcategories
Worker	Freedom of Association and Collective Bargaining
	Child Labour
	Fair Salary
	Working Hours
	Forced Labour
	Equal opportunities/Discrimination
	Health and Safety
Consumer	Health & Safety
	Feedback Mechanism
	Consumer Privacy
	Transparency
	End of life responsibility
Local Community	Access to material resources
	Access to immaterial resources
	Delocalization and Migration
	Cultural Heritage
	Safe & healthy living conditions
	Respect of indigenous rights
	Community engagement
	Local employment
	Secure living conditions
Society	Public commitments to sustainability issues
	Contribution to economic development
	Prevention & mitigation of armed conflicts
	Technology development
	Corruption
Value Chain Actors	Fair competition
	Promoting social responsibility
	Supplier relationships
	Respect of intellectual property rights

2.2.4 Indicators in Social Life Cycle Assessment

According to UNEP/SETAC (2009), inventory indicators can be described as specific definitions of the data sought, and they are considered the most direct evidence of the condition or result of what is intended to be measured.

Indicators can be quantitative, semi-quantitative or qualitative. Some social impacts can be better captured using quantitative indicators, while others may be better captured by semiquantitative or qualitative indicators. Thereby, the type of indicator to be used on the assessment depends on the goal of the study and the nature of the issue to be addressed (UNEP/SETAC, 2009).

The quantitative indicators use numerical information to describe an issue and are based on quantifiable data. On the contrary, qualitative indicators are measured through data that cannot be directly presented numerically. These indicators are nominative, which means that they use words and descriptive text to describe an issue (Lúcio, 2017). Finally, the semiquantitative indicators result from the categorization of qualitative information into a yes/no form or a scale (scoring system). These indicators are measured through data collected in the form of questionnaires with "yes" or "no" responses, or, rating scale responses (UNEP/SETAC, 2009, 2013). They are often used to understand the perception that stakeholders have regarding the behavior of the organization.

As shown in Figure 2.3, another aspect that can be considered in the characterization of the indicators is the direction of impact. This idea was originally stated by van Haaster et al. (2017), who consider that the indicators may have a positive or negative desired direction for sustainability, depending on the nature of the social impact being measured.

Social impacts can directly affect, positively or negatively, the organization's stakeholders (Benoît et al., 2010). Thus, indicators with a positive desired direction for sustainability such as Employee work satisfaction or Percentage of the workforce hired locally, are used to measure the social impacts that affect the stakeholders in a positive way (van Haaster et al., 2017). On the other hand, the indicators with a negative desired direction for sustainability are used to measure the social impacts that negatively affect the stakeholders. Examples of such indicators are the Number of occupational accidents, Gender pay gap, and Presence of child labor.

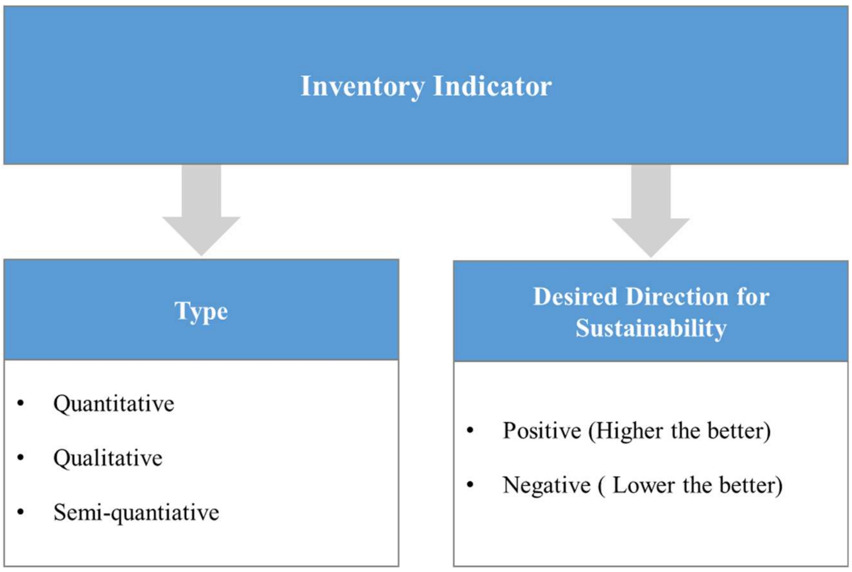


Figure 2.3 - Characteristics of an inventory indicator

The main source of social indicators is the UNEP/SETAC Methodological sheets for Subcategories in Social Life Cycle Assessment (UNEP/SETAC, 2013). It provides a list of more than 100 inventory indicators to assess each subcategory. Moreover, it identifies whether data are available in quantitative, semi-quantitative, or qualitative type and provide data sources for each indicator.

Kühnen and Hahn (2017) identified and analyzed 141 papers to study trends, consistencies, and gaps in research on the SLCA indicators. The authors argue that researchers should select the minimum set of the most important social indicators to assess the stakeholders based on empirical experience instead of common sense, across all industry sectors. On the basis of the review, they identified the most addressed subcategories and indicators to assess each stakeholder category. Regarding the stakeholder Value Chain Actors, most of the studies used indicators that deal with promoting social responsibility among value chain actors, to verify the supplier's compliance with human rights. To assess the stakeholder Consumer, the researchers typically used indicators to measure the consumer's health and safety. Similarly, most of the researchers addressed health and safety when assessing the stakeholder Worker. Regarding the stakeholder Society, most of the researchers focus on the contribution to economic development by quantitatively measuring, the number of employees, full-time employee hours and employment stability. Lastly, the most addressed subcategory concerning the stakeholder Local Community is safe and healthy living conditions. To assess this subcategory, researchers use qualitative indicators to describe potential accident risks and quantitative indicators to measure local morbidity. Table 2.4 provides an overview of the most frequently addressed SLCA indicators according to Kühnen and Hahn (2017).

2.2.5 Data sources, types and collection methods

Indicators can be described as specific definitions of the data to be collected (Hosseinijou et al., 2014). That being said, it is certain that when considering a quantitative indicator, the data used to measure the indicator must also be quantitative (numerical information). Consequently, when using qualitative indicators, the data used to measure the indicator must be qualitative (descriptive text). Moreover, the same reasoning naturally applies to semiquantitative indicators.

According to UNEP/SETAC (2009), data can also be site-specific or generic. Site-specific data corresponds to the data collected specifically from the organization involved in the value chain of the product under assessment. Data collected on site allows analyzing the relationship between an organization and its stakeholders. Data can also be generic, which means that this data can be collected from the country, region or sector in which the organizations of the product value chain make their activities and processes (UNEP/SETAC, 2009).

Ciroth and Franze (2011) stated that both site-specific data and generic data should be considered when conducting a SLCA study. Site-specific data is essential for the investigation of a specific product or organization. Nevertheless, generic data is also important, since it can be used as a reference value for the organization performance. For instance, the wage level of an organization only makes sense when compared to the wage level in the country where the organization operates (Ciroth & Franze, 2011).

Table 2.4 - Overview of the most addressed Social Life Cycle Assessment indicators

Adapted from Kühnen and Hahn (2017)

Subcategories	Indicators	Typical measurement approach	Indicators objectives
Safe and healthy living conditions in local communities	Potential of accident risks	Narrative description	Potential of accident risks aims at anticipation and prevention of future accidents. Local morbidity and human health depreciation aim at retrospective correction of business operations with negative health impacts on local community members
	Local morbidity and human health depreciation	Disability adjusted life years (DALYs) of local community members	
Promoting social responsibility among value chain actors	Supplier's compliance with human rights and codes of conduct	Verification on a semiquantitative yes/no scale	Indicators aim at promoting social responsibility by monitoring obligation of upstream and downstream value–chain actors to respect basic human rights in their business operations and eventually take corrective actions
	Screening of suppliers on human rights	Number and percentage of actors screened	
Consumer's health and safety	Product health and safety	Consumer-related toxicity potential as measured in ELCA; DALYs of consumers	Indicators related to consumers aim at measuring health damages when customers and consumer use a product.
	Injuries, diseases, and fatalities	Number or percentage of affected consumers	
Worker's health and safety	Occupational health and safety	Worker related toxicity potential as measured in ELCA; DALYs of workers	Indicators related to workers aim at measuring health damages when workers pursue their occupation
	Injuries, diseases, and fatalities	Number or percentage of affected workers	
Contribution to society's economic development	Employees and full-time equivalent employment	Number or percentage of full-time employees	Indicators aim to assess how companies generate jobs in countries where supply–chain operations take place
	Employment stability	Number and ratio of hires and dismissals	
Other	Stakeholder's satisfaction	Only generically mentioned	Indicators aim at assessing subjective experiences or feelings of impacted stakeholders.
	Stakeholder's sensory and aesthetic perceptions	Only generically mentioned	

There may be several different methods for collecting data that can be used, depending on the type and source of data being collected. When it comes to site-specific data, methods such as the audit of the reports and documentation provided by the organization, interviews and stakeholders surveys, or the observations during field visits, can be used to collect data in the organizations involved in the product life cycle (UNEP/SETAC, 2009). On the other hand, generic data can be obtained by statistical data, collected from national statistical agencies or international databases, like the Eurostat database, the International Labour Organization (ILO) database and the Organisation for Economic Cooperation and Development (OECD) database.

2.2.6 Social Life Cycle Assessment case studies

Different applications of the SLCA methodology can be found in the literature. Petti et al. (2016) carried out a systematic review of the literature in SLCA, where they identified 34 case studies, published between 2010 and 2014, that have used SLCA for different purposes. Most of the studies applied the SLCA to a wide range of products, such as roses (Franze & Ciroth, 2011), notebook (Ciroth & Franze, 2011), laptop computer (Ekener-Petersen & Finnveden, 2013), cheese (Paragahawewa, Blackett, & Small, 2009), milk (Rev, Couture, & Parent, 2015), used polyethylene terephthalate (PET) bottles (Foolmaun & Ramjeeawon, 2013), waste recycling systems (Aparcana & Salhofer, 2013a), fertilizers (Martínez-Blanco et al., 2014), building materials (Hosseinijou et al., 2014), biodiesel (Macombe et al., 2013; Manik, Leahy, & Halog, 2013) and photovoltaic modules (Traverso, Asdrubali, Francia, & Finkbeiner, 2012). While others applied the methodology to study the social performance of different companies and industry sectors, including integrated circuit packaging companies (Wang, Hsu, & Hu, 2017), Indian steel sector (Singh & Gupta, 2017), Italian textile sector (Lenzo et al., 2017), furniture sector (Bork et al., 2015), sugar industry (Prasara-A & Gheewala, 2018), Italian wine sector (Arcese, Lucchetti, & Massa, 2017) and tourism sector (Arcese, Lucchetti, & Merli, 2013).

As there is no specific impact assessment method provided in the UNEP/SETAC guidelines that can be used to measure and aggregate the data in a SLCA study, it was necessary to develop an impact assessment method according to the needs and characteristics of the present study. For that purpose, 4 of the case studies mentioned above (Ciroth & Franze, 2011; Foolmaun & Ramjeeawon, 2013; Singh & Gupta, 2017; Wang, Hsu, & Hu, 2016) were used as a foundation for developing the methodology proposed in this study. The four case studies were selected according to their applicability and relevance to the goals and objectives of the present study and are described below.

Table 2.5 provides an overview of the selected case studies and gives a brief description of the impact assessment method developed in each case study. Specific parts of the impact assessment methods proposed by the authors will be used and adapted for the development of the SLCA methodology proposed in this study.

Table 2.5 - Overview of the selected Social Life Cycle Assessment case studies

Reference	Object of study	Goals of the study	Life Cycle stages	Stakeholders	Subcategories and indicators	Social impact assessment method used in the study
Ciroth and Franze (2011)	Notebook	Identify social hotspots in the entire life cycle	Cradle to grave (all life cycle stages are considered)	Workers Local comm. Society Value chain actors Consumers	31 subcategories, 85 indicators	A color system, with six colors, is used to assess the performances and impacts of the companies. A specific factor, between 1 and 6, is then assigned to each color, in order to allow the quantification of the performance and impacts. In this method, international standards are used as Performance Reference Points (PRPs) to compare the performance of the companies with the situation in the country or region into account.
Foolmaun and Ramjeeawon (2013)	Polyethylene terephthalate bottles	Compare the social impacts of disposal alternatives	Grave to grave (only End-of-life is considered)	Workers Society Local community	8 subcategories, 11 indicators	In this method, the data required to measure the subcategories indicators are collected through questionnaires with "yes" or "no" questions. Through the conversion of the questionnaire's answers into percentages, a score between 0 and 4 is assigned to each indicator by classifying the percentage obtained into five categories of percentage (0–20, 21–40 , 41–60, 61–80 and 81–100). The scores obtained for each subcategory are summed up into a final single score for each disposal scenario.
Wang et al. (2016)	Integrated circuit packaging companies	Analyse the social impact of three production sites for semiconductor packaging in Taiwan	Gate to gate (only Manufacturing Stage)	Workers	7 subcategories, 19 indicators	Scoring systems for quantitative and semiquantitative indicators are proposed. For each quantitative indicator a score of 1 to 5 is assigned, according to the proportion between the data collected in the factories and the statistical data at the country or sector level. For the semiquantitative indicators, management efforts on social performance, within five elements (i.e. policy, measure, communication, response, and record) are assessed according to three levels of implementation. The consistent fuzzy preference relations method is then employed to determine the weights of each indicator. The final score of each factory is obtained by the summation of the scores of each indicator multiplied by its weight.
Singh and Gupta (2017)	Indian steel sector	Identify social hotspots in the value chain of steel products	Cradle to grave (all life cycle stages are considered)	Workers Local comm. Society Value chain actors Consumers	20 subcategories, 25 indicators	Indicators are divided into 3 groups according to the data collection method. Some are measured through data regarding the social conditions of the geographical locations of the companies (group 1), others are measured through quantitative data (group 2), and others depend on the implementation level of policies (group 3). In this method, a score between 1 and 4, is assigned to each indicator. The scores are first aggregated at the indicator level and then at the stakeholder category level. The sum of the five stakeholder categories scores gives the aggregated score for each of the 5 life cycle stages, ranging from 0,25 to 1. The final score of the product is given by the summation of the life cycle stages scores, in a range from 1 to 5.

The literature review carried out for the present study also showed that, to date, there is not any study that has applied the SLCA methodology to study the social impacts of products made by AM technology.

1) LCA of an Ecolabeled Notebook: Consideration of Social and Environmental Impacts Along the Entire Life Cycle (Ciroth & Franze, 2011)

Ciroth and Franze (2011) proposed their impact assessment method to study the social and environmental impacts of an eco-labeled notebook throughout its life cycle. Their approach consists of two phases. The first one assesses the performance of the company/sector based on Performance Reference Points. They compare the performance of the sectors/companies engaged in the notebook life cycle with the performance in the country or region where the companies/sector are. The major reference points used in the study were the International Labour Organization (ILO) conventions, ISO 26000 guidelines, and the OECD Guidelines for Multinational Enterprises. The second phase assesses the impacts of the company/sector behavior with regard to the impact categories proposed in the UNEP Guidelines (2009). Each subcategory of a stakeholder was assessed twice, i.e., for the performance of a company and the impacts of the company, based on a color rating scale. This color scale consists of six shades colors, where green, light green, bluish green, yellow, orange and red, means very good performance/positive impact, good performance/lightly positive impact, satisfactory performance/indifferent impact, inadequate performance/lightly negative impact, poor performance/negative impact and very poor performance/very negative impact, respectively. A specific factor, between 1 and 6, is then assigned to each color to allow the quantification of the performance and impacts. The resulting score for each stakeholder category was the average of the assigned factors of its subcategories. Finally, social hotspots (orange and red color) are identified in every life cycle stage of the notebook to facilitate its comparison with different product alternatives.

2) Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius (Foolmaun & Ramjeeawon, 2013)

Foolmaun and Ramjeeawon (2013) developed another assessment method to compare the environmental and social impacts of four disposal alternatives for used PET bottles. This method aims to convert qualitative inventory information into quantitative inventory data and then aggregate the data using a scoring system. The data required to measure the subcategories indicators are collected through questionnaires employed to the relevant stakeholders, consisting of “yes” or “no” type questions. The answers of the questionnaires are then converted into percentages for each indicator. A score, between 0 and 4, is then assigned to each subcategory, by classifying the percentages into one of the five categories of percentage namely: 0–20 %, 21–40 %, 41–60 %, 61–80 % and 81–100 %. For the subcategories having more than one indicator, the final score of the subcategories corresponds to the average of the indicators scores considered in the subcategory. Finally, the scores obtained for each subcategory are summed up into a single score to facilitate the comparison among different disposal alternatives.

3) An analytic framework for social life cycle impact assessment - part 1: methodology (Wang, Hsu, & Hu, 2016)

Wang et al. (2016) used quantitative and semiquantitative indicators to assess the social impacts of three factories in the electronics sector in Taiwan on their workers. In the method proposed by the authors, data collection methods and scoring systems are determined for each type of indicators. Regarding the quantitative indicators, available social statistical data from the government is used as performance reference points to reflect the situation in the country or sector level in which the companies operate. For each indicator, social impact percentage is calculated, according to the proportion between the data collected in the three factories and the statistical data at the country or sector level in Taiwan. A score of 1 to 5 is then assigned to each quantitative indicator by classifying the social impact percentage into nine categories of percentage. For the positive impact indicators, a score of 1 to 5, within nine levels corresponds to a proportion of less than 25, 25 to 50, 50 to 75, 75 to 100, 100, 100 to 125, 125 to 150, 150 to 175, and more than 175 %, respectively. On the contrary, for the negative impact indicators, a score of 1 to 5, within nine levels corresponds to a proportion of more than 175, 150 to 175, 125 to 150, 100 to 125, 100, 75 to 100, 50 to 75, 25 to 50, and less than 25 %, respectively. For the semiquantitative indicators, the authors proposed a method that considers five elements, namely policy, measure, communication, response, and record, to assess the management efforts of the companies on social performance. For each of the five elements, the management efforts are categorized into three degrees, namely, not implemented (score of 0), partially implemented (score of 0.5), and fully implemented (score of 1). The results of the five elements are combined into an aggregated score for each semiquantitative indicator. The authors used consistent fuzzy preference relations method to determine the weights of each indicator according to the opinion of ten experts. The score is subsequently multiplied by the weight of each indicator from the CFPR method, and a final social impact score is obtained for each of the three factories.

4) Social life cycle assessment in Indian steel sector: a case study (Singh & Gupta, 2017)

Singh and Gupta (2017) developed an impact assessment method to study the social impacts of steel products manufactured by an Indian company. In their approach, the indicators were divided into three groups on the basis of data collection methods. In the first group of indicators, social condition indicators such as water availability, infrastructure, electricity, education, safe living conditions, are used to assess the social conditions of the regions where the companies involved in the product life cycle operate. Available national data regarding these social conditions in India were collected from government databases. A score of 1 to 4 is assigned to each indicator, by comparing the social data of the locality or region where the company is settled with the social data of the country. For the second group of indicators, a score ranging from 1 to 4 is assigned to each indicator. Specific assessment criteria are defined for each indicator on the basis of judgment and through consultation with the company management. These indicators are quantitative and are measured through quantitative data collected from the companies engaged in the product's value chain. For the third group of indicators, a questionnaire was carried out to the respondents, in order to obtained responses on the basis of their perception of documentation of policies, level of deployment, monitoring and review mechanism in place. For the five life cycle stages considered in the study, i.e., raw materials, transport, manufacturing, customer and end-of-life, the scores provided by the respondents for each indicator are aggregated first ate the indicator level and then at the stakeholder category level. The sum of the five stakeholder categories score gives an aggregated score for each life cycle stage, ranging from 0.25 to 1. Aggregating these values for the five life cycle stages gives the overall final score of the product, in a range from 1 to 5.

2.2.7 Application Challenges

The SLCA methodology is relatively new in the context of sustainability assessment, and few studies were conducted to test the feasibility of the methodology. The publication of the UNEP/SETAC Guidelines and its complementary methodological sheets was considered a cornerstone in SLCA development (Traverso, Bell, Saling, & Fontes, 2016). These guidelines provide a methodological framework and propose several subcategories, indicators and data sources to measure the respective indicators. However, the guidelines do not provide any specific impact assessment method that can be used to measure and aggregate the data across the life cycle of the product. The lack of a standardized impact assessment method motivated several authors to develop their approaches to address this gap. This has caused a proliferation of different impact assessment methods that can be found in the literature (Petti et al., 2016). Furthermore, despite the wide range of indicators proposed in the guidelines, there is a considerable disparity between the number of indicators provided for each stakeholder (Prasara-A & Gheewala, 2018). Many indicators can be used to assess the stakeholder Worker, whereas, for the remaining categories of stakeholders (Consumer, Local Community, Society and Value Chain Actors) there are much less available choices of subcategories and indicators.

As discussed in the work of Petti et al. (2016), another methodological issue in SLCA is the difficulty in relating social effects to the functional unit (FU). This is mainly due to the fact that social impacts are not directly connected to the processes and activities necessary to produce the product, but instead, they are related to the conduct and behavior of the organizations engaged in the product's value chain. These issues contribute to a lower degree of causality between the social impacts and the product itself (Jørgensen, 2010).

Regarding the selection of indicators, Ciroth and Franze (2011) discuss that can be a very arduous task to select an appropriate set of indicators that can illustrate the specific situation under assessment while addressing the stated goal of the study at the same time. The authors also claim that there is not a default set of subcategories and indicators that can be adapted to different needs.

The limitations mentioned above are mainly due to the very nature of social phenomena and their effects (UNEP/SETAC, 2009). Although environmental impacts are easy to quantify, since most of them are measured by numerical data (emissions and energy consumption), the same is not true for social impacts. In most cases, numeric information is not sufficient or even appropriate to address the social impacts, due to their qualitative nature (UNEP/SETAC, 2009). The need to incorporate qualitative data in SLCA makes it quite difficult to quantify the impacts and aggregate them throughout the product life cycle (Paragahawewa et al., 2009). Also, the assessment of social impacts can be very subjective, as cultural aspects, personal values and lifestyles may affect the way social problems are perceived (Lenzo et al., 2017). This dependence on subjective value choices means that the assessment of the social impacts will always be linked to an inherent and inevitable subjectivity (Ciroth & Franze, 2011).

Chapter 3: Social Life Cycle Assessment methodology development

In this chapter, a SLCA methodology will be proposed to study the social impacts of products produced using AM technology. The first part will be designated to provide an overview of the proposed methodology and its development steps. Then, each one of the necessary steps for the development of the methodology will be described in detail. In the end, a brief explanation of the computational application model developed to implement the proposed SLCA methodology will also be provided.

3.1 Overview

In order to assess the social impacts of a product produced by AM technology, an SLCA methodology is proposed based on the UNEP/SETAC guidelines and in the four case studies (Ciroth & Franze, 2011; Foolmaun & Ramjeeawon, 2013; Singh & Gupta, 2017; Wang et al., 2016) identified and analysed in Chapter 2. The methods developed by these authors were used and adapted for the development of the proposed methodology, more specifically, in the calculation of the indicators, in the scoring system and the aggregation of the indicators scores. The methodology follows the four SLCA phases, described in Chapter 2, and aims to assess the social impacts of an AM product across its whole life cycle. As a result, it is intended to provide a clearer perception of both positive and negative social impacts associated with a product produced by AM technology.

Figure 3.1 provides the framework used to develop the SLCA methodology. It considers a set of indicators to measure the social impacts of an AM product on different subcategories, stakeholder categories, and life cycle stages. These indicators are then aggregated to obtain a unique score that translates the social impacts of a product produced by AM technology.

The SLCA methodology considers the social impacts of products from a life cycle perspective (Wang et al., 2016). This means that the social impacts of a given product are investigated and assessed at each stage of the product life cycle, since its extraction to its disposal.

The matching of the social impacts with the people and social groups affected by them, i.e., the stakeholders, corresponds to the starting point of the framework. For this purpose, it is necessary to determine within each life cycle stage, which types of stakeholders can be affected by the social interaction with the AM product. As there are several types of stakeholders, UNEP/SETAC (2009) considers clusters of stakeholders that have shared interests due to their similar relationship to the investigated product. In order to facilitate the matching between social impacts and its stakeholders, it

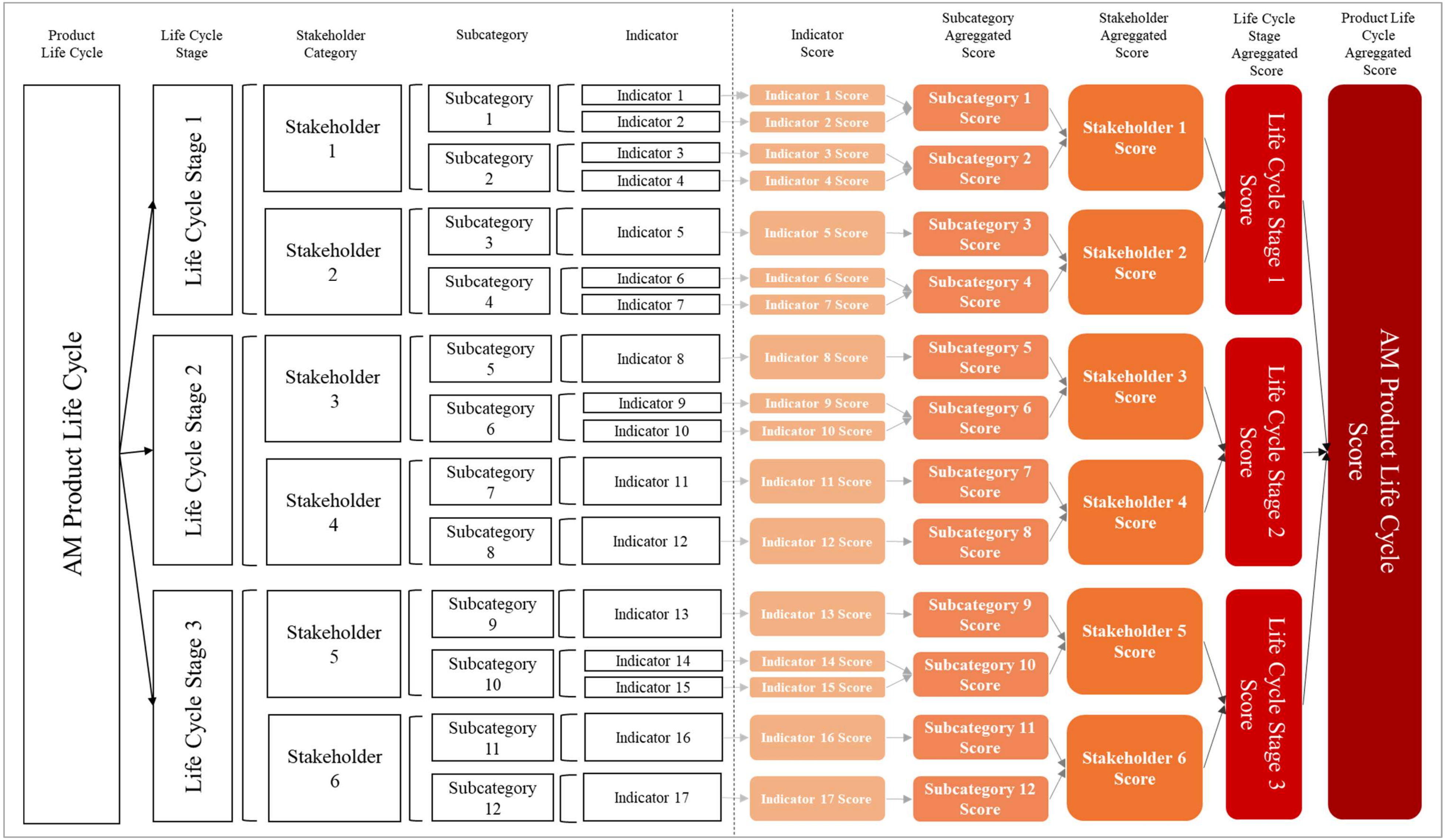


Figure 3.1 - Framework to assess the social impacts of an Additive Manufacturing product

is also necessary to identify in which contexts these stakeholders can be affected. This way, the stakeholder categories are divided into several subcategories, which according to Benoît et al. (2010) are socially significant issues of interest to stakeholders such as human rights, working conditions, poverty, disease, political conflict, among others.

The assessment of social impacts is conducted by means of indicators related to each subcategory (Macombe et al., 2013). These indicators are measured through social data and can be qualitative, quantitative or semiquantitative, depending on the type of data used to measure the indicator (Benoît et al., 2010). In the proposed methodology, the selection of indicators was performed according to their relevance and applicability to the context of AM. Some of these indicators were screened from the work of Ribeiro (2017), in which the author developed several social indicators to assess the social impacts of the AM technology. These indicators are specific to AM technology. Due to the small number of indicators proposed by Ribeiro (2017) and the difficulty in adapting these indicators to the proposed methodology, generic social indicators suggested in SLCA literature were also considered. However, further research is necessary regarding their applicability within the social context of AM technology.

Following the selection of the stakeholders, subcategories, and indicators, it is necessary to define how the results of the indicators will be calculated, aggregated and interpreted throughout the product life cycle. A score between 1 and 5 is assigned to each indicator, according to the relevance of the data collected to measure each indicator. The indicator scores are then aggregated at each level of the assessment to arrive at the single aggregated value that corresponds to the final score of the AM product life cycle.

The aggregation method proposed in this study follows the approach of Singh and Gupta (2017). The indicators results are aggregated first at the subcategory level, then at the stakeholder level and finally at the life cycle stage level (Figure 3.1). The aggregation of the life cycle stages scores gives the final score of the AM product life cycle, in a range between 1 and 5. A score of 5 corresponds to a highly positive social impact, and a score of 1 corresponds to a highly negative social impact.

3.2 Methodology Development

The UNEP/SETAC guidelines for SLCA and its complementary methodological sheets were the main references for developing the SLCA methodology for AM products. The four main phases of the SLCA methodology were adapted to address the thesis objectives. The proposed methodology presented in this study consists of six major steps, as shown in Figure 3.2. The first step of the approach consisted of the identification of the goals of the study and the life cycle stages that would be used to assess the social impacts of the AM product. Then, the stakeholder categories, subcategories, and indicators were selected according to their relevance to the context of AM technology. Indicators groups were also defined according to the type, source and collection method of the data used to measure the indicators. For the impact assessment, calculation methods and scoring systems for each indicators group were developed. Moreover, it was also necessary to establish a method that could aggregate the indicators scores into a final single value that corresponded to the product life cycle score. In the last step of the approach, it was identified how the social impacts would be classified and interpreted according to the obtained scores.

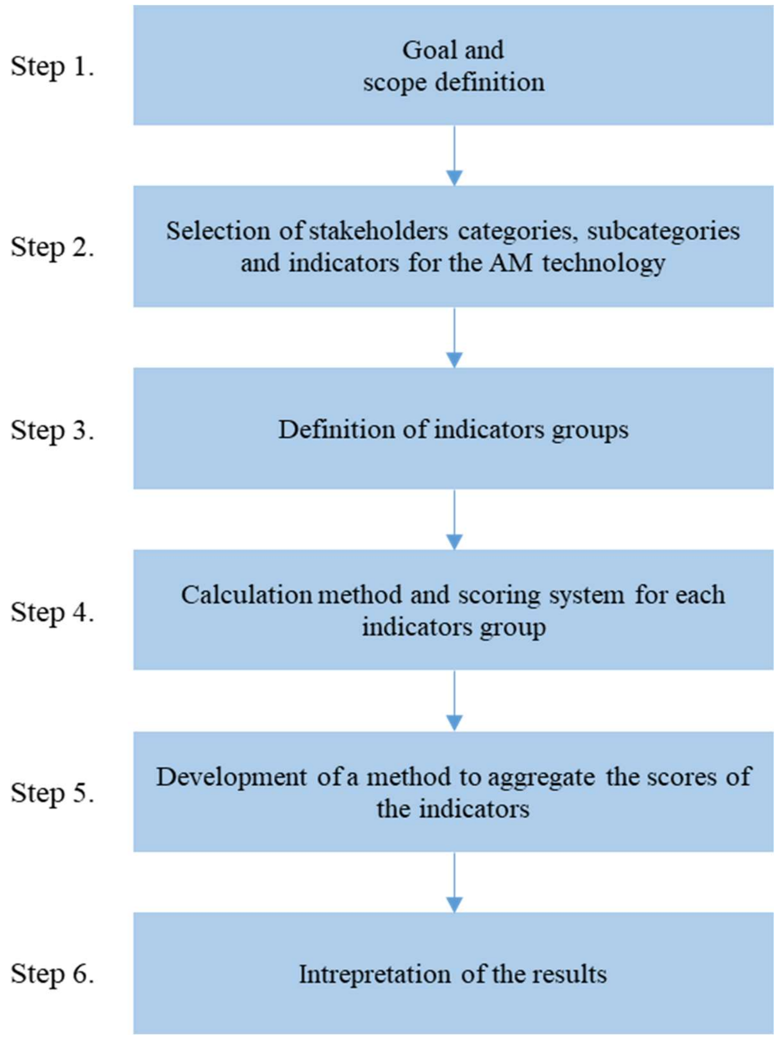


Figure 3.2 - Steps of the proposed methodology

In order to develop this methodology, the following assumptions were also stated:

- The social impacts of the AM product are determined through the assessment of the social performance of the organizations involved in the value chain of the product (Singh & Gupta, 2017). This is mainly due to the fact that social impacts are not directly connected to the processes and activities necessary to make the product, but instead, they are related to the conduct and behavior of the organizations engaged in the product's value chain. For instance, to assess the social impacts of the Manufacturing stage of the product, social data should be collected from the organization who produces the final AM product. On another hand, when considering the Raw Materials stage, the social data should be collected from the organization that provides the raw material necessary to fabricate the final AM product.

- All stakeholders are affected in each life cycle stage. However, in a real case setting this cannot be applied and therefore, a selection of the stakeholders affected within each life cycle stage must be carried out. By doing so, different stakeholders will be considered in each life cycle stage. For instance, in the Use stage of the product, probably the only stakeholder affected by interacting with the product is the Consumer, thereby, when conducting a case study, this is the only stakeholder considered in the Use stage.
- All stages of the AM product life cycle are of equal relevance to the present study, and as such, for calculation purposes, all carry equal weights. Furthermore, within each life cycle stage, all the indicators have also equal weights. The main reason for not assigning different weights to the indicators was to keep the approach as simple as possible due to the pilot nature of this study.

The next sections of this chapter will be designated to explain in detail each of the steps shown in Figure 3.2.

3.3 Goal and scope definition

The main goal of the methodology is to provide a quantitative method to assess the social impacts of a product produced by AM technology, throughout its whole life cycle. According to Benoît et al. (2010), social impacts can be very difficult to interpret and measure, because they often rely on subjective data collected from the perception of stakeholders. As a result, most of the social indicators suggested in the SLCA literature, to measure the social impact of a product, are both qualitative or semiquantitative. Thereby, it becomes more difficult to develop new approaches that enable the aggregation of these types of indicators into a single final score, that can demonstrate the social impact of a product. The methodology presented here aims to provide a method that can aggregate the results provided by the indicators, into figures, according to a scoring system. With this, it is possible to quantify the social impacts and even classify them into different levels of impact.

In the scope definition, the limits are defined on the AM product's life cycle. The majority of the studies in SLCA found in the literature, adopt a "cradle to grave" approach in which all life cycle stages are included, since extraction to disposal. Although Product Design is not considered an important stage in the life cycle of a product produced by conventional manufacturing processes, in AM this stage represents a large part of the product life cycle, playing a key role for the development of the AM product. Designers have to make many decisions at the Product Design stage, regarding the dimensions and materials of the product, which will have a very significant impact on the other life cycles stages (Ma et al., 2018). For these reasons, this study also includes the Product Design stage in the assessment.

Thus, in this study a "conception to grave" (Ma et al., 2018) life cycle point of view is adopted, in which the AM product life cycle can be divided into five main stages (Figure 3.3):

- **Product design:** The Product Design stage focuses on product architecture design and planning. It involves the 3D product modeling through CAD technology, the product material selection, and the manufacturing process design;
- **Raw materials production:** This stage focuses on the production of the raw materials needed to manufacture the final product. It involves the production of the powders, resins or other materials that can be used in the different types of AM processes;
- **Manufacturing stage:** Corresponds to the fabrication of the final product through an AM process. It includes: 1) Preparation of the process; 2) 3D Printing of the product; 3) Post Processing (e.g., surfaces, edges), 4) Part Assembly (when necessary);
- **Use stage:** The use stage begins with the use of the product by the consumers and ends when the product is out of usage;
- **End-of-life stage:** It involves the reuse, remanufacturing, repair, recycle or disposal of the product.

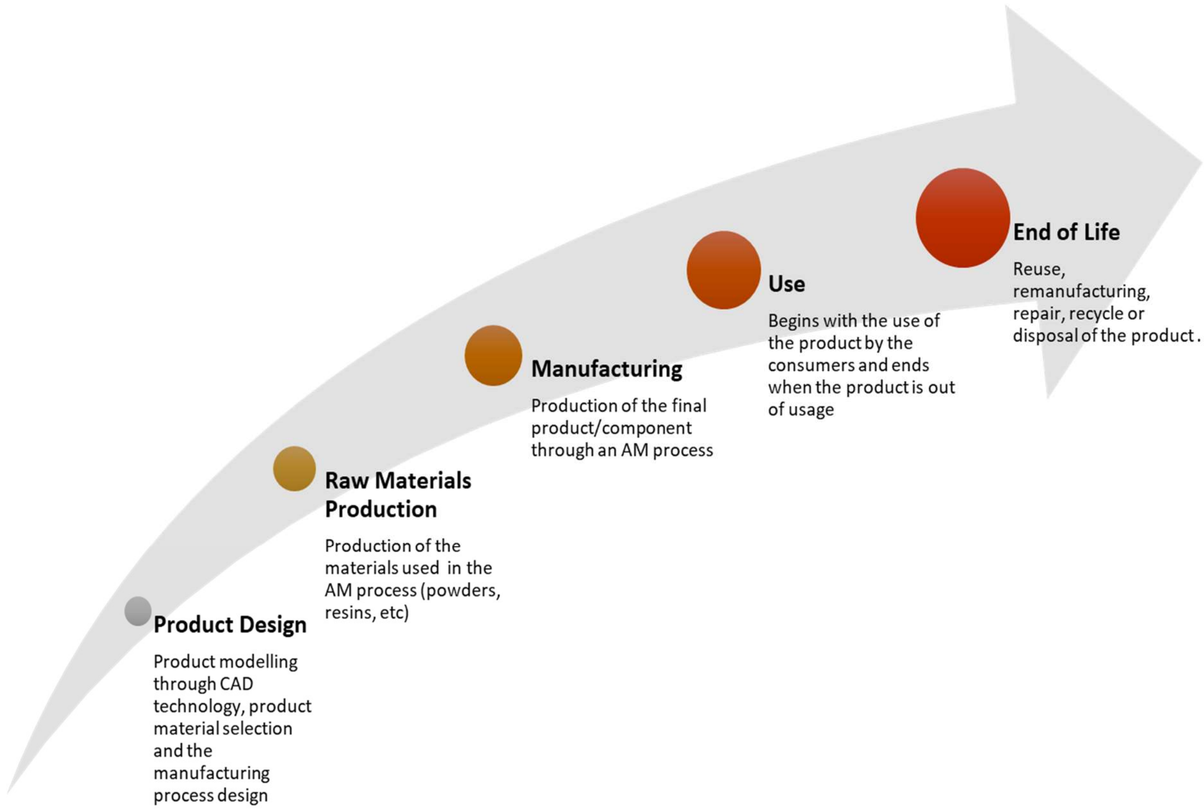


Figure 3.3 - Life Cycle stages considered in the methodology

3.4 Selection of stakeholder categories, subcategories and indicators for the AM technology

In this section, the stakeholders, subcategories and indicators will be selected according to their relevance to the context of AM technology. First, the stakeholder categories and subcategories will be selected according to Table 2.3. Then, indicators screened from the work of Ribeiro (2017) and the Methodological sheets for Social Life Cycle Assessment (UNEP/SETAC, 2013) will be proposed for each subcategory and stakeholder category.

3.4.1 Stakeholder categories

The stakeholder categories can be defined as groups of stakeholders with shared interests due to their connection to the product under assessment (UNEP/SETAC, 2009). Within each life cycle stage of the product defined in the previous section, there will be different stakeholders that will be affected in different ways when interacting with the product. In this approach, the five main stakeholder categories stated in the UNEP/SETAC guidelines will be considered. They are as follows:

- Workers/Employees.
- Local Community
- Society
- Consumer
- Value chain actors

Since there is yet no detailed studies in the literature review regarding the social impacts of AM, this study pretends to first study the social impacts of an AM product only within the stakeholder categories defined in Table 2.3. Nevertheless, after future research on the subject, other stakeholder categories like future generations might be included in the methodology.

3.4.2 Subcategories

Table 2.3 provides the indication of the subcategories that could be considered in a SLCA study. In some cases, the use of certain subcategories may not be relevant according to the legislation or social context of the country in which the product life cycle is being assessed. For instance, it is quite clear that the stakeholder subcategory “Respect of Indigenous Rights” does not bring any relevance if the assessment is carried out in countries in which there is not any evidence of indigenous people and communities within the country's territory.

Due to the pilot nature of this study, and the limited time and resources of this research, the methodology proposed does not consider all the subcategories from the list provided by UNEP/SETAC (2013). This methodology also considers the subcategory of Psychological working conditions. The idea of expanding the analysis on workers beyond the physical wellbeing has first worked by Jørgensen et al. (2008) and then developed by Aparcana and Salhofer (2013) who included in their study the assessment of psychological conditions of workers. This subcategory is strictly related to the work satisfaction within the workforce, and its demonstrated by the willingness of workers to continue fulfilling the same function and/or to continue working in the same organization (Arcese et al., 2017).

Table 3.1 presents all the 15 subcategories, distributed by the five stakeholder categories, considered in this study. As observed, each stakeholder category can be associated with several different subcategories.

Table 3.1 – Stakeholder categories and subcategories selected to assess the social impacts of Additive Manufacturing technology

Stakeholder Category	**Subcategory**
Worker	Health and safety Working Hours Fair Salary Child Labour Equal Opportunities/Discrimination Phycological Working conditions Social Benefit /Social Security
Local Community	Local Employment Access to immaterial resources
Society	Prevention and Mitigation of Conflicts
Value Chain Actors	Respect of Intellectual Property Rights Supplier Relationships Promoting Social Responsibility
Consumer	Health and safety Privacy

3.4.3 Indicators

In this study, the indicators are classified according to their type, i.e., quantitative, qualitative or semi-quantitative, and to their desired direction for sustainability. The social indicators were chosen based on a review of the literature on the social aspects of the AM technology and previous studies related to the application of the SLCA methodology in the assessment of the social impacts of different products. As shown in Chapter 2, the study of the social impacts of the AM technology is still at an early stage, and as such, very few indicators that can measure the social impacts of this technology have been proposed. Ribeiro (2017) studied the social aspects of the AM technology and proposed a set of 20 indicators, specific to the technology, to assess the social impacts of AM on the five stakeholders defined in the UNEP/SETAC guidelines. Some of the indicators proposed by Ribeiro (2017) were screened and adapted for the needs of the present study. The selection was performed according to their relevance and applicability in this study and to the data availability. Since there are few specific indicators for the AM technology found in the literature, other indicators were also considered in this study. These indicators were screened from the list provided in the methodological sheets (UNEP/SETAC, 2013) and from previous case studies applied in the study of different types of products.

Table 3.2 shows the set of indicators selected to assess the social impacts of AM technology. The indicators are presented for each stakeholder category and subcategory and are classified according to their type, i.e., quantitative, semi-quantitative or qualitative, and desired direction for sustainability A total of 26 indicators have been proposed, 14 are relative to the stakeholder Worker, 4 to the Local community, 3 to the Value chain actors, 1 to the Society and 4 to the Consumer. Only 1 indicator has been selected for the stakeholder Society because there is a lack of information regarding this category in SLCA literature and very few indicators have been proposed to assess it. Moreover, it is also possible to verify that of the 26 indicators, 18 are quantitative, and 8 are semi-quantitative.

3.5 Definition of indicators groups

In this section, an overview of the data collection process that is required to measure the indicators will be presented. Questions such as "What type of data should be used?", "Where should the data be collected?" and "What method should be used to collect the data?" are some of the questions that will be explained in detail in this subsection. In the end, indicators groups are defined according to the data collection methods used for each of them.

The data necessary to measure the selected indicators in the previous subsection is mainly site-specific. Most of the indicators considered in this study are calculated through data collected directly from the organizations engaged in the AM product life cycle. However, for some indicators, generic data is also considered when comparing the performance of the organization with the country or sector context.

For each group, a calculation method and a scoring system to assess the indicator results are proposed. A summary of the data collection methodology for the four groups of indicators is presented in Table 3.3. The indicators groups are presented according to data type, data source, and data collection method.

Table 3.2 - Indicators selected

Stakeholder	Subcategory	Nº	Indicator	Indicator Description	Type	Desired Direction
Worker	Health and safety	1	Non-Fatal occupational accidents incidence rate [a,b]	Reveals the number of non-fatal occupational accidents amongst the organization's workforce, per year per 100000 employees [c]	Quantitative	Negative
		2	Fatal occupational accidents incidence rate [a,b]	Reveals the number of fatal occupational accidents amongst the organization's workforce, per year per 100000 employees [c]	Quantitative	Negative
		3	Use of Personal Protective Equipment (PPE) [a]	This indicator shows the level of use of PPE by the workers, in the workplaces and situations in which their use is mandatory. It can demonstrate the organization's lack of training, control, and awareness for the importance of the use of PPE's	Semi-quantitative	Positive
		4	Preventive measures and emergency protocols regarding accidents and injuries [a,b]	This indicator reveals the competence of the measures taken to ensure the well-being of the workforce [a,b]	Semi-quantitative	Positive
	Equal opportunities/ Discrimination	5	Presence of female employees in management positions [d]	It shows the percentage of female employees in management positions in relation to all employees in management positions [d]	Quantitative	Positive
		6	Gender pay gap [e]	The objective of this indicator is to assess the evidence of wage discrimination between male and female employees. It reveals the difference between average gross hourly earnings of male and female employees as % of male gross earnings [e]	Quantitative	Negative
	Fair salary	7	Average monthly basic remuneration of employees [d]	Reveals the average remuneration per month per full-time employee [d]	Quantitative	Positive
		8	Percentage of employees receiving minimum wages [f]	Reveals the percentage of employees who receive the minimum wage defined by law in the country where the organization is.	Quantitative	Negative
	Psychological working conditions	9	Employee work satisfaction [g]	It reveals the level of satisfaction of the employees regarding their job and also their willingness to continue working in the same organization. [g]	Semi-quantitative	Positive
	Working hours	10	Average weekly hours of work by full-time employee [d]	Average working hours per week (includes overtime) per full-time employee [d]	Quantitative	Negative
	Child labor	11	Presence of child labor in the organization [a]	Describes the percentage of children working in the organization below legal age or 15 years old [a]	Quantitative	Negative
	Social benefit /Social security	12	Access to legal social benefits [g]	This indicator shows if all the social benefits according to the country laws are being given to the workers [g]	Quantitative	Positive
		13	Percentage of workers educated by the organization regarding AM technology [b]	Describes the percentage of workers within the organization who received training about the technology [b]	Quantitative	Positive
		14	Percentage of qualified workers in the organization [b]	Describes the percentage of workers within the organization that are qualified [b]	Quantitative	Positive

Table 3.2 - Indicators selected (cont.)

Stakeholder	Subcategory	Nº	Indicator	Indicator Description	Type	Desired Direction
Local community	Local employment	15	Percentage of the workforce hired locally [ab]	It shows the ratio of the workforce that are from the local community [b]	Quantitative	Positive
		16	Percentage of spending on locally-based suppliers [a]	Describes the percentage of spending off annual budget on locally based suppliers [g]	Quantitative	Positive
		17	Percentage of Local suppliers	This indicator reveals the number of the organization's suppliers that are from the local community	Quantitative	Positive
	Access to immaterial resources	18	Organization's efforts in promoting AM education initiatives in the local community [b]	This indicator measures the efforts of the organization in promoting the AM technology within the local community, through education initiatives [b]	Semi-quantitative	Positive
Value chain actors	Promoting social responsibility	19	Integration of ethical, social and environmental criteria in purchasing and distribution policy [a]	The goal of this indicator is to understand the efforts made by the organization to integrate the social criteria in decision making regarding purchasing and distribution policy [a]	Semi-quantitative	Positive
	Respect of intellectual property rights	20	Organization's policy and practice regarding the protection of intellectual properties rights [ab]	This indicator shows the competence of the efforts made by the organization in the protection of intellectual properties rights	Semi-quantitative	Positive
	Supplier Relationships	21	Payments on time to suppliers [a]	It reveals the percentage of suppliers who have been paid for the service provided until the date of the study	Quantitative	Positive
Society	Prevention and Mitigation of Conflicts	22	Organizations' efforts to prevent the manufacturing of weapons using AM [b]	The goal of the indicator is to assess the efforts made by the organization to regulate and prevent the production of weapons using AM technology [b]	Semi-quantitative	Positive
Consumer	Health and safety	23	Organization's efforts and measures to protect consumer health and safety [a]	This indicator reveals the competence of the efforts and measures taken to ensure the well-being of the consumer [a]	Semi-quantitative	Positive
		24	Percentage of consumers negatively affected regarding their health and safety [a]	Reveals the percentage of the consumers who complained about the negative effects of the use of the product regarding their health and safety within the last year	Quantitative	Negative
	Privacy	25	Organization's efforts and measures to ensure the protection of consumer privacy [a]	This indicator demonstrates the efforts and measures developed by the organization to ensure the security of personal data that they collect, store or process	Semi-quantitative	Positive
		26	Percentage of the consumers affected by situations of breach of privacy or loss of data [a]	Describes the percentage of the consumers who complained about situations of privacy breach or loss of data within the last year	Quantitative	Negative

Sources: [a] UNEP (2013), [b] Ribeiro (2017), [c] Eurostat (2013), [d] Siebert et al. (2018), [e] Leythienne and Ronkowski (2018), [f] Singh and Gupta (2017), [g] Aparcana and Salhofer (2013)

In Group 1, the indicators are associated with quantities, percentages or rates, and are used to measure the performance of the organization by comparing it with the performance at the country level or sector level in which the organization operates. For this purpose, a method was developed based on the approach of Wang et al. (2016), that consists of using available social data from government statistics as Performance Reference Points (PRP) to determine the social impact exerted by the organizations. Thus, the indicator is first measured from data collected in the organization through documentation or reports (site-specific data) provided by the organization. Then, the result value from this measure is compared to the PRP (generic data) which is collected from national statistical agencies or international databases, like the ILO database and OECD reports. That value can be either above or below the PRP and according to that, a final result is given to the indicator. Indicators such as "Fatal occupational incidence rate", "Gender pay gap" or the "Presence of female employees on a management position" are some of the indicators considered in this group.

In Group 2, indicators are also associated with quantities, percentages or rates. They measure the significance and breadth of the impact, for example, through the "number/percentage of people affected" positively or negatively by the impact. However, in this group, indicators are not compared with the PRP (country or sector data), because they are related to social topics on which national statistical databases are not yet very developed. As such, the results of these indicators are further compared with a reference scale adapted from the work of Foolmaun and Ramjeeawon (2013). The data used in this group is site-specific, therefore, must be collected from documentation or reports provided by the organization under assessment.

For Group 3, a method is developed according to the work of Wang et al. (2016). In this approach, the semiquantitative indicators are used to assess the strength of the efforts and measures taken by the organization regarding social issues. To assess these management efforts, five elements are considered: Policy, Communication, Deployment, Monitoring, and Response. Management interviews, documentation and reports provided by the organization are used to assess each one of these elements. Data collected from observations during field visits may also be used to understanding whether efforts and measures are being applied to the organization's daily work or not (UNEP/SETAC, 2009).

Lastly, in Group 4, the indicators assess the behavior of the organization engaged in the life cycle of the product, towards the stakeholders who are affected by their activities (Dreyer, Hauschild, & Schierbeck, 2010). In order to do that, a questionnaire is carried out to the specific stakeholders affected by the organization in the social issue being studied. Responses are collected in the form of a five-point response scale from the respondents, on the basis of their perception of the organization's behavior regarding the social issue in question.

Table 3.3 - Indicators groups and their data collection methodology

Group	**Group description**	**Data type**	**Data source**	**Data collection method**
Group 1	The indicators are associated with quantities, percentages or rates, and are used to measure the performance of the organization by comparing it with the performance at the country level or sector level in which the organization operates (Wang et al., 2016). In this approach, statistical data at the country or sector level is used as a performance reference point (PRP) to assess the social impacts.	Quantitative	Site-specific and generic data (PRP)	Documentation/reports provided by the organization and National statistical data collected from national statistical agencies or international databases
Group 2	The indicators are also associated with quantities, percentages or rates. However, they are not compared with country or national data (PRP), because they are related to social topics on which national statistical databases are not yet very developed. As such, the results are further compared with a reference scale adapted from the work of Foolmaun and Ramjeeawon (2013).	Quantitative	Site-specific	Documentation and reports provided by the organization.
Group 3	The indicators are used to assess the strength of the efforts and measures taken by the organization regarding social issues (Wang et al., 2016). To assess these management efforts, five elements are considered: Policy, Communication, Deployment, Monitoring, and Response.	Semi quantitative	Site-specific	Management interviews, documentation and reports provided by the organization and observations during field visits
Group 4	The indicators measure the behavior of the organization towards its stakeholders (Dreyer et al., 2010), through questionnaires carried out to the stakeholders affected by the organization activities. Responses are collected in the form of a five-point response scale from the respondents, on the basis of their perception of the organization's behavior regarding the social issue in question.	Semi-quantitative	Site-specific	Stakeholders questionnaires with a five-point response scale.

Table 3.4 matches the 26 proposed indicators to the four indicator groups. As it is possible to verify, 7 of the proposed indicators belong to Group 1, 10 to Group 2, 7 to Group 3 and 2 to Group 4.

Table 3.4 - Allocation of the indicators to the four indicators groups

Stakeholder	Subcategory	Nº	Indicator	Group
Worker	Health and safety	1	Non-Fatal occupational accidents incidence rate	Group 1
		2	Fatal occupational accidents incidence rate	Group 1
		3	Use of Personal Protective Equipment (PPE)	Group 4
		4	Preventive measures and emergency protocols regarding accidents and injuries	Group 3
	Equal Opportunities /Discrimination	5	Presence of female employees in management positions	Group 1
		6	Gender pay gap	Group 1
	Fair Salary	7	Average monthly basic remuneration of employees	Group 1
		8	Percentage of employees receiving minimum wages	Group 1
	Psychological Working Conditions	9	Employee work satisfaction	Group 4
	Working Hours	10	Average weekly hours of work by full-time employee	Group 1
	Child Labour	11	Presence of child labor in the organization	Group 2
	Social Benefit /Social Security	12	Access to legal social benefits	Group 2
		13	Percentage of workers educated by the organization regarding AM technology	Group 2
		14	Percentage of qualified workers in the organization	Group 2
Local Community	Local Employment	15	Percentage of the workforce hired locally	Group 2
		16	Percentage of spending on locally-based suppliers	Group 2
		17	Percentage of local suppliers	Group 2
	Access to immaterial resources	18	Organization's efforts in promoting AM education initiatives in the local community	Group 3
Value Chain Actors	Promoting Social Responsibility	19	Integration of ethical, social and environmental criterions in purchasing and distribution policy	Group 3
	Respect of Intellectual Property Rights	20	Organization’s policy and practice regarding the protection of intellectual properties rights	Group 3
	Supplier Relationships	21	Payments on time to suppliers	Group 2
Society	Prevention and Mitigation of Conflicts	22	Organizations’ efforts to prevent the manufacturing of armed conflicts weapons using AM	Group 3
Consumer	Health and Safety	23	Percentage of consumers negatively affected regarding their health and safety	Group 2
		24	Organization's efforts and measures to protect consumer health and safety	Group 3
	Privacy	25	Percentage of the consumers affected by situations of breach of privacy or loss of data	Group 2
		26	Organization's efforts and measures to ensure the protection of consumer privacy	Group 3

3.6 Calculation method and scoring system for each indicators group

In this section, the calculation method and scoring system will be developed for each group of indicators defined in the previous section, which means that within each group of indicators, the indicators are all calculated in the same way and are evaluated with the same scoring system. A score between 1 and 5 is assigned to each indicator, based on the data collected and the scoring criteria defined to measure the indicator. A score of 5 corresponds to the best possible score, and a score of 1 corresponds to the worst possible score. Although the score range (1 to 5) is the same for all the indicators, the scoring criteria are different for each group of indicators. Furthermore, the scores assigned to the indicators can have different meanings according to the desired direction of sustainability of each indicator. For instance, when considering an indicator with negative direction for sustainability such as fatal accident incidence rate, the bigger the number of fatal accidents, the lower is the score assigned to the indicator because the goal is to have the minimal number of accidents in the organization. On the other hand, when considering an indicator with positive desired direction for sustainability, for instance, the average remuneration level in the organization, the higher the average remuneration level in the organization, the bigger is the score assigned to the indicator. That being said, different scoring systems within each group of indicators are proposed according to the desired direction for sustainability of the indicators.

3.6.1 Group 1 Indicators

In this group, national statistical data is used as a PRP to assess the organization social performance. The calculation method and the scoring system developed for these indicators are based on the approach of Wang et al. (2016), that consists of the following steps:

1. Collecting data from the organization;
2. Collecting national statistical data at country or sector level in which the organization operates, this is the PRP;
3. Calculate the social impact percentage that corresponds to the proportion between the two different types of data;
4. Assigning a score of 1 to 5, within nine levels according to the social impact percentage calculated and the desired direction for sustainability of the indicator.

In summary, the first step consists of collecting data from the organization to measure the indicator. Then, statistical data from the country or sector in which the organization operates (PRP) is also collected to compare with the data collected from the organization. Following the data collection, a social impact percentage is calculated to demonstrate the proportion between the two types of data, as shown in equation 3.1.

$$\text{Social impact \%} = \frac{\text{Data collected}}{\text{PRP}} \times 100 \qquad \text{(eq. 3.1)}$$

Where PRP stands for statistical data at country or sector level.

A score of 1 to 5, within nine levels (i.e., 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5) is then assigned to the indicator, according to the fill-in of the social impact percentage calculated within the nine social impact percentages categories (0 to 25, 25 to 50, 50 to 75, 75 to 100, 100, 100 to 125, 125 to 150, 150 to 175, and more than 175). Two scoring systems are proposed, one for the indicators with positive desired direction for sustainability, and other for the indicators with negative desired direction for sustainability (Table 3.5).

An example of the calculation method for Group 1 indicators, is described and illustrated in Annex A.

Table 3.5 - Scoring System for Group 1 indicators

		Social impact percentage (%)								
	Desired direction for sustainability	<25	25 - 50	50 – 75	75 – 100	100	100 – 125	125 - 150	150 - 175	>175
Score	Positive	1	1,5	2	2,5	3	3,5	4	4,5	5
	Negative	5	4,5	4	3,5	3	2,5	2	1,5	1

3.6.2 Group 2 Indicators

These indicators measure the significance and breadth of the impact, for example, through the number/percentage of people affected positively or negatively by the impact. The calculation method and the scoring system developed for these indicators follows the approach of Foolmaun and Ramjeeawon (2013). In this group, indicators are not compared with country or sector data, because they are related to social topics on which national statistical databases are not yet very developed. Instead, the percentages calculated through the data collected in the organization are classified into five categories of percentage namely: 0–20 %, 20–40 %, 40–60 %, 60–80 % and 80–100 %.

In summary, the calculation and the assigning of scores to each indicator in this group can be described in the following steps:

1. Collecting data from the organization regarding the social theme assessed by the indicator;
2. Calculate the indicator in the form of a percentage, through the data collected in the organization;
3. Classification of the percentages obtained in the previous step in one of the five categories of percentage (0–20 %, 20–40 %, 40–60 %, 60–80 % and 80–100 %) according to the desired direction for sustainability of the indicator. Two scoring systems are proposed, one for the

indicators with positive desired direction for sustainability, and other for the indicators with negative desired direction for sustainability (Table 3.6).

An example of the calculation method for Group 2 indicators, is described and illustrated in Annex B.

Table 3.6 - Scoring System for Group 2 indicators

		Percentage (%)				
	Desired direction for sustainability	0 – 20	20 – 40	40 – 60	60 – 80	80 – 100
Score	Positive	1	2	3	4	5
	Negative	5	4	3	2	1

3.6.3 Group 3 Indicators

The semi-quantitative indicators in Group 3 are used to assess the strength of the efforts and measures taken by the organizations regarding social performance. The calculation method and the scoring system developed for these indicators are based on the approach of Wang et al. (2016) and Dreyer et al. (2010). To assess the management efforts of the organization, five elements are considered: Policy, Communication, Deployment, Monitoring and Response (Table 3.7). For each one of these elements, a score of 0.2, 0.6 and 1 is assigned, according to its level of implementation in the organization, which can be "Not implemented", "Partially implemented" and "Fully implemented". The final score of the indicator ranges between 1 and 5 and is given by the sum of the scores of each element.

In summary, the calculation method can be described in the following steps:

1. Collecting data through documentation provided by the organization, interviews with managers, and observations during field visits in the organization facilities;
2. Analysis of the data collected for each element;
3. According to the analysis of the data collected, a score of 0.2 (not implemented), 0.6 (partially implemented) and 1 (fully implemented) is assigned to each element;
4. The final score of the indicator, between 1 and 5, corresponds to the sum of the scores of each one of the 5 elements.

Table 3.7 shows the scoring system used to assess these indicators, and also provides a detailed description of each one of the five elements considered in the method.

An example of the calculation method for Group 3 indicators, is described and illustrated in Annex C.

Table 3.7 - Scoring System for Group 3 indicators

Adapted from Wang et al. (2016)

Elements	**Efforts**	**Level of Implementation**	**Score**
Policy	Establishment of practices or policies that address and support the integration of the measure in the organization	Not implemented	0.2
		Partially implemented	0.6
		Fully implemented	1
Communication	Communication of commitment for the compliance with the measure to employees, managers and other relevant stakeholders across his value chain	Not implemented	0.2
		Partially implemented	0.6
		Fully implemented	1
Deployment	The measure has been implemented in every required situation	Not implemented	0.2
		Partially implemented	0.6
		Fully implemented	1
Monitoring	Performance of continuous control to ensure that managers and employees comply with the established measure	Not implemented	0.2
		Partially implemented	0.6
		Fully implemented	1
Response	A review mechanism for handling complaints and suggestions has been established to ensure response	Not implemented	0.2
		Partially implemented	0.6
		Fully implemented	1

3.6.4 Group 4 Indicators

The indicators in Group 4 assess the behavior of the organization engaged in the life cycle of the product, towards the stakeholders affected by their activities (Dreyer et al., 2010). In this dissertation is proposed the following calculation method. First, it is necessary to collect data from questionnaires addressed to the stakeholders affected by the organization in the social impact under study. The respondents must respond on the basis of their perception of the organization's behavior regarding the social impact in question, according to the five-point response scale presented in Table 3.8. Each one of the five scores corresponds to a description of the perception of the stakeholder. The score of 1 is considered the worst scenario, while the score of 5 corresponds to the best possible scenario.

Table 3.8 - Scoring system for Group 4 indicators

Score	Response
1	The worst scenario
2	…
3	…
4	…
5	The best scenario

After collecting the results of the questionnaire, the weighted average is calculated through equation 3.2, to determine the final score of the indicator.

$$\bar{X} = \frac{\sum_{i=1}^{n} V_i \times W_i}{\sum_{i=1}^{n} W_i} \qquad \text{(eq.3.2)}$$

Where,

$\bar{X}$ is the weighted average;

W_i is the number of stakeholders interviewed who attributed the score i to the indicator;

V_i is the score i attributed to the indicator by the stakeholders in the questionnaire.

The final score of the indicator corresponds to the exact value of the weighted average calculated in the previous step.

An example of the calculation method for Group 4 indicators, is described and illustrated in Annex D.

3.7 Development of a method to aggregate the scores of the indicators

Following the determination of the calculation method and scoring system for each group of indicators, it is necessary to define a mathematical method to aggregate the scores of the indicators into a single final score that corresponds to the product life cycle score. In this methodology, the scores are aggregated at each level of the assessment, i.e., subcategory, stakeholder category, life cycle stage and finally, product life cycle. Figure 3.4 considers the manufacturing life cycle stage to exemplify how the aggregation method works. As shown, the indicators scores are aggregated first at the subcategory level, and then at the stakeholder level. The sum of the stakeholder categories aggregated scores gives a single score for the life cycle stage, in this case, the Manufacturing stage. The same procedure is applied to obtain the other life cycle stages' scores of the AM product.

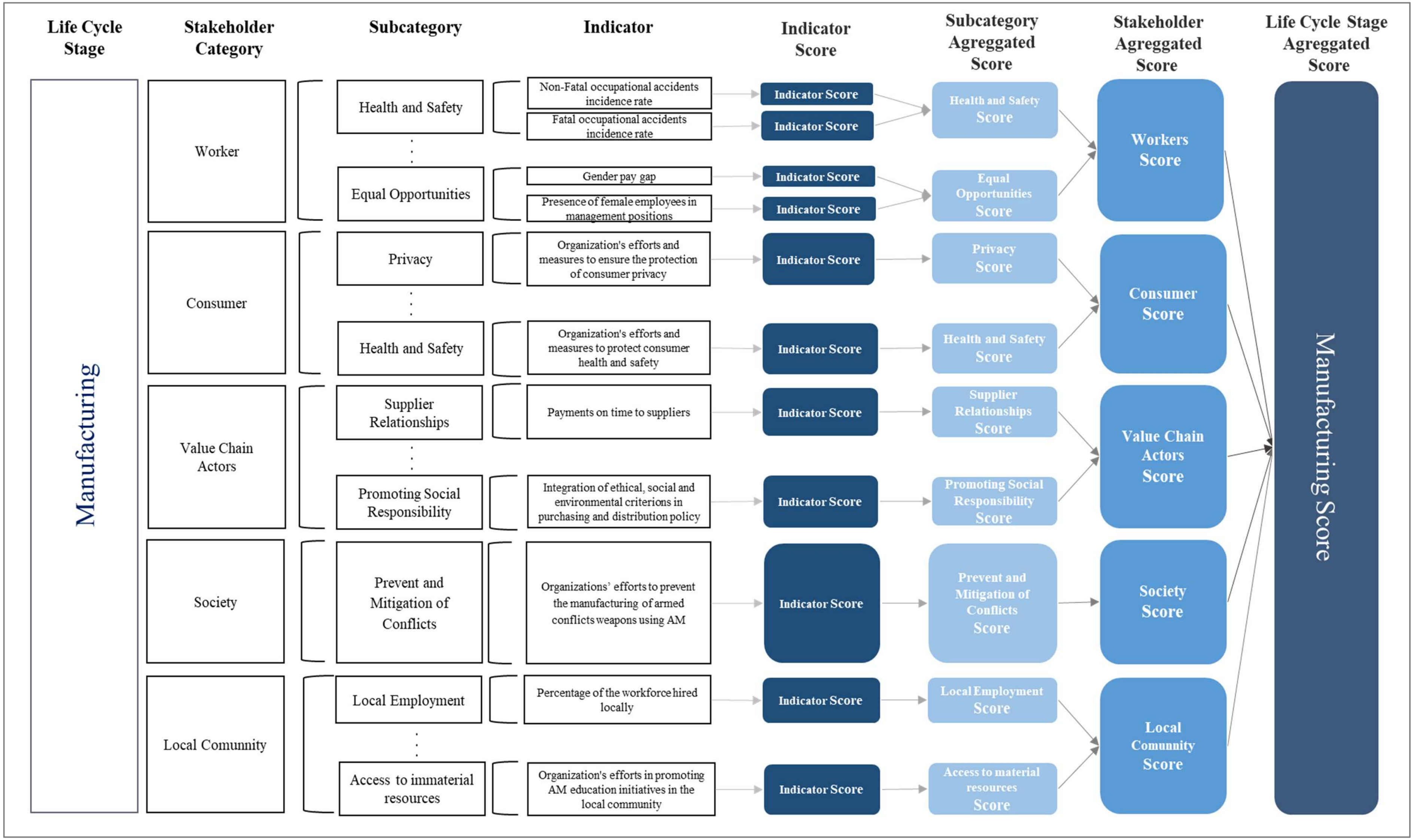


Figure 3.4 - Aggregation of scores for the Manufacturing Stage

Finally, the scores of each life cycle stage considered in the study, i.e., Product Design score, Raw Materials Production score, Manufacturing score, Use score, and End of Life score are aggregated into an overall score that corresponds to the AM product life cycle score, as shown in Figure 3.5. This final aggregated score can assume values between 1 and 5 and demonstrates the social impact of the AM product towards its stakeholders.

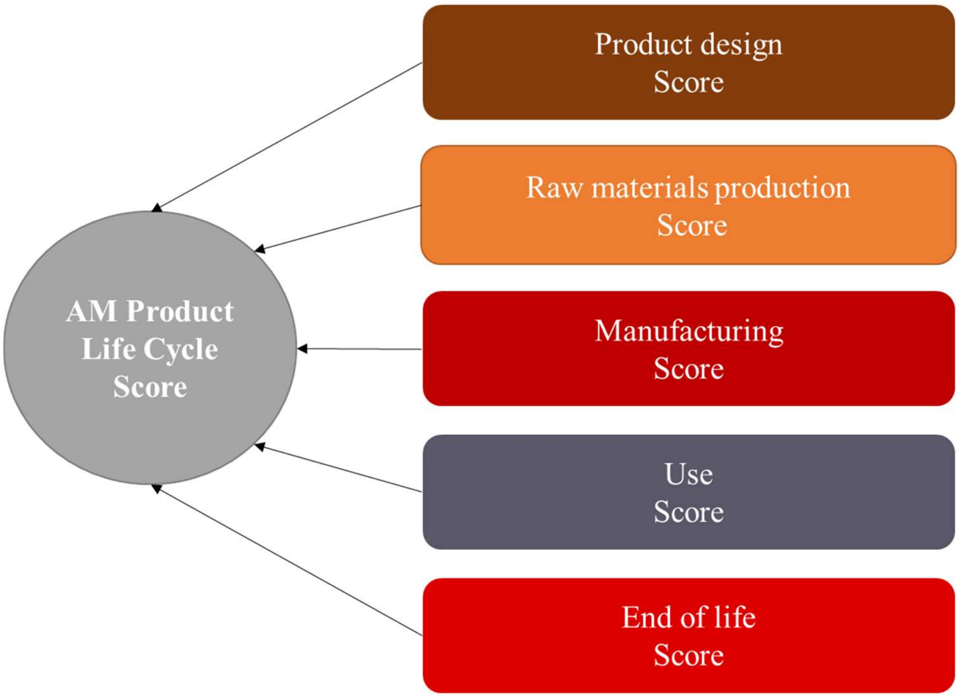


Figure 3.5 - Aggregation of scores for the Additive Manufacturing product life cycle

Step 5 of the proposed methodology requires a mathematical method to aggregate the different scores along the assessment. The aggregation method developed in the present study follows the approach of Singh and Gupta (2017), in which the authors developed an aggregation method to conduct a social assessment of the Indian steel sector. In this approach, equal weights are assigned to each indicator. The indicators scores are normalized by multiplying the scores with the indicators weights. The resulting normalized scores are then aggregated within each life cycle stage by summing up the scores of the respective stakeholder categories. In this way, a score between 0.2 and 1 is assigned to each life cycle stage. The final score of the AM product social impact equates the summation of the life cycle stages scores, which gives a possible score between 1 and 5.

Figure 3.6 illustrates the aggregation method proposed in this study. The method comprises the following steps:

Step 1: Definition of the indicator weights

The first step is to determine the indicators weights. As previously stated in section 3.2, equal weights are assigned to the indicators within each life cycle stage. The main reason for not assigning different weights to the indicators was to keep the approach as simple as possible due to the pilot nature of the study.

As shown in equation 3.3, the weight of each indicator is obtained by dividing 1 by the total number of indicators considered in each life cycle stage.

$$\text{Indicator i Weight} = \frac{1}{\text{Number of Indicators considered in the life cycle stage}} \qquad \text{(eq. 3.3)}$$

In section 3.2, it was also defined that all the stakeholders considered are affected in each life cycle stage, and as such, the number of indicators used to assess each life cycle stage will also be the same. This means that the indicators considered in the study will all have the same weight in any of the life cycle stages of the product. Since 26 indicators are used to assess each life cycle stage, the weight of each indicator will be 0.0385 (Figure 3.6). However, when conducting a case study, a selection of the stakeholders affected in each life cycle stage is required. By doing so, the number of stakeholders affected in each life cycle will be different, and consequently, the number of indicators in each life cycle will also be different. Since the weight of the indicators depends on the number of indicators considered in each life cycle, the indicators considered in different life cycle stages can have different weights. For example, in a life cycle stage in which a larger number of stakeholders are affected, the number of indicators considered will be higher and consequently, the weight of each indicator will be lower. On the other hand, when considering a life cycle stage in which few stakeholders are affected, there will be a smaller number of indicators and, consequently, the weight of each indicator will be higher.

Step 2: Normalizing the indicator score

Following the score assigning and the definition of the indicator weight, the indicators scores must be normalized. As shown in equation 3.4, the indicator normalized score $(\mathrm{e})_\mathrm{i}$ is obtained by multiplying the indicator score with the indicator weight and dividing by five, which corresponds to the maximum score value that can be assigned to an indicator.

$$(\mathrm{e})_\mathrm{i} = \frac{\text{Indicator i weight} \times \text{Score i}}{5} \qquad \text{(eq. 3.4)}$$

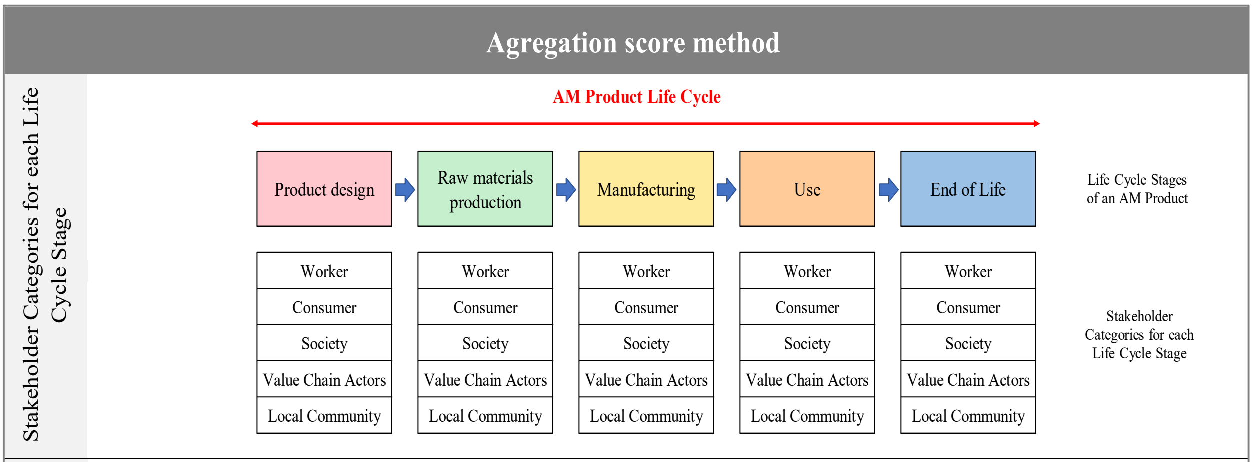
Where,

$(\mathrm{e})_\mathrm{i}$ is the indicator i normalized score;

Indicator i weight is the weight assigned to the indicator i;

Score i is the score assigned to the indicator i;

Agregation score method



Aggregation of scores within each Life Cycle Stage

Stakeholder category	Subcategory	Number of Indicators Subcategory (a)	Number of Indicators Stakeholder Category (b)	Indicator Weight (c) $\frac{1}{\sum(b)_i}$	Scoring Scale (d) min	Scoring Scale (d) max	Normalized Indicator Score Range (e) min $\frac{(c)*(d=1)}{5}$	Normalized Indicator Score Range (e) max $\frac{(c)*(d=5)}{5}$	Subcategory Agregated Score (f)	Min – Max Subcategory Aggregated Score (min)	Min – Max Subcategory Aggregated Score (max)	Stakeholder Category Agregated Score (g)	Min – Max Stakeholder Category Aggregated Score (min)	Min – Max Stakeholder Category Aggregated Score (max)
Worker	Health and safety	4	14	0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{4}(e)_i$	0,0308	0,1538	$\sum_{i=1}^{14}(f)_i$	0,1077	0,5385
	Equal opportunities	2		0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{2}(e)_i$	0,0154	0,0769			
	Phsycological working contitions	1		0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{1}(e)_i$	0,0077	0,0385			
	Fair salary	2		0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{2}(e)_i$	0,0154	0,0769			
	Working hours	1		0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{1}(e)_i$	0,0077	0,0385			
	Child Labour	1		0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{1}(e)_i$	0,0077	0,0385			
	Social benefit /Social security	3		0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{3}(e)_i$	0,0231	0,1154			
Local community	Local employment	3	4	0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{3}(e)_i$	0,0231	0,1154	$\sum_{i=1}^{4}(f)_i$	0,0308	0,1538
	Access to immaterial resources	1		0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{1}(e)_i$	0,0077	0,0385			
Value chain actors	Respect of Intellectual Property Rights	1	3	0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{1}(e)_i$	0,0077	0,0385	$\sum_{i=1}^{3}(f)_i$	0,0231	0,1154
	Supplier Relationships	1		0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{1}(e)_i$	0,0077	0,0385			
	Promoting Social Responsibility	1		0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{1}(e)_i$	0,0077	0,0385			
Society	Prevent and Mitigation of Conflicts	1	1	0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{1}(e)_i$	0,0077	0,0385	$\sum_{i=1}^{1}(f)_i$	0,0077	0,0385
Consumer	Health and safety	2	4	0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{2}(e)_i$	0,0154	0,0769	$\sum_{i=1}^{4}(f)_i$	0,0308	0,1538
	Privacy	2		0,0385	1	5	0,0077	0,0385	$\sum_{i=1}^{2}(e)_i$	0,0154	0,0769			
			26						Min - Max Score for each Life Cycle Stage				0,2	1,0
			Total										Min	Max

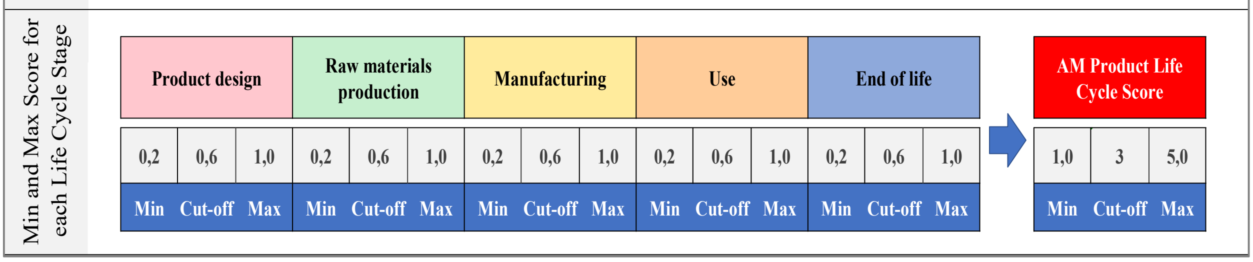


Figure 3.6 - Aggregation score method

Adapted from Singh and Gupta (2017)

Since the scoring scale for each indicator is set between 1 and 5, the minimum value for the Normalized Indicator Score, is $\frac{\text{Indicator i weight} \times 1}{5}$, and the maximum value for the Normalized Indicator Score is $\frac{\text{Indicator i weight} \times 5}{5}$. These values show the range of possible values for the indicator normalized score when conducting a case study.

Step 3: Aggregating the indicators scores at the subcategory level

Once the scores are normalized, the aggregation process can begin. The indicators scores are first aggregated at the subcategory level. As shown in equation 3.5, the subcategory aggregated score $(f)_i$ is given by the summation of the normalized indicators scores used to assess the respective subcategory.

For instance, the aggregated score of the subcategory "Fair salary", related to the stakeholder "Worker", corresponds to the sum of the normalized scores of the two indicators used to assess this subcategory, as can be seen in Figure 3.6.

$$(f)_i = \sum_{i=1}^{n} (e)_i \qquad \text{(eq. 3.5)}$$

Where,

$(f)_i$ is the subcategory i aggregated score;

$(e)_i$ is the indicator i normalized score used to assess the subcategory;

n is the number of indicators used to assess the subcategory.

The minimum possible score for the subcategory is obtained by multiplying the number of indicators used to assess the subcategory with the minimum possible value for the normalized indicator score. On the contrary, the maximum possible score for the subcategory is obtained by multiplying the number of indicators used to assess the subcategory with the maximum possible value for the normalized indicator score. For instance, the minimum and maximum possible score for the subcategory "Fair salary" in the stakeholder "Worker", corresponds to 0.0154 and 0.0769, respectively, as shown in Figure 3.6.

Step 4: Aggregating of the subcategories scores into stakeholder category scores

This step consists of aggregating the subcategories scores into stakeholder categories aggregated scores. In order to do that, the equation 3.6 is applied. The stakeholder category aggregated score $(g)_i$ is given by the summation of the subcategories aggregated scores that are related to the stakeholder category. For instance, the aggregated score of the stakeholder "Consumer" is given by the sum of the subcategories "Health and Safety" and "Privacy" aggregated scores.

$$(g)_i = \sum_{i=1}^{n} (f)_i \qquad \text{(eq. 3.6)}$$

Where,

$(g)_i$ is the stakeholder category i aggregated score;

$(f)_i$ is the subcategory i aggregated score associated with the stakeholder category;

n is the number of subcategories associated with the stakeholder category.

The minimum possible score for the stakeholder category is obtained by multiplying the number of indicators used to assess the stakeholder category with the minimum possible value for the normalized indicator score. On the contrary, the maximum possible score for the stakeholder category is obtained by multiplying the number of indicators used to assess the stakeholder category with the maximum possible value for the normalized indicator score. For example, the minimum and maximum possible score for the stakeholder "Consumer", corresponds to 0.0308 and 0.1538, respectively, as shown in Figure 3.6.

Step 5: Life cycle stage aggregated score

Within each life cycle stage, different stakeholders can be affected by the interaction with the product. Thus, the life cycle stage aggregated score $(h)_i$ is given by the summation of the aggregated scores of the stakeholders affected in the life cycle stage, as shown in equation 3.7.

$$(h)_i = \sum_{i=1}^{n} (g)_i \qquad \text{(eq. 3.7)}$$

Where,

$(h)_i$ is the life cycle stage i aggregated score;

$(g)_i$ is the stakeholder category i aggregated score affected in the life cycle stage;

n is the number of stakeholder categories affected in the life cycle stage.

The aggregation of the stakeholder categories scores results in a score ranging between 0.2 and 1 for each life cycle stage, as shown in Figure 3.6. A score of 0.2 corresponds to the minimum possible score for each life cycle stage and is obtained if all the indicators are assigned a score of 1. On the other hand, a score of 1 corresponds to the maximum possible score for each life cycle stage and is obtained if all the indicators are assigned a score of 5. Since all the indicators scores are normalized for each life cycle stage in step 2, the minimum and maximum scores for each life cycle stage will always be 0.2 and 1, regardless of the number of indicators and stakeholder categories considered in each life cycle stage.

Step 6: AM product life cycle final score

The last step of the method consists of aggregating the life cycle stages aggregated scores into the single final score of the AM product life cycle. As shown in equation 3.8, the product life cycle final score is given by the summation of the life cycle stages aggregated scores considered in the product life cycle.

$$\text{AM Product Life cycle final score} = \sum_{i=1}^{n} (h)_i \qquad \text{(eq. 3.8)}$$

Where,

$(h)_i$ is the life cycle stage i aggregated score considered in the AM product life cycle;

n is the number of life cycle stages considered in the AM product life cycle.

In this study, it is considered that the AM product life cycle comprehends five distinct life cycle stages (Product design, Raw materials production, Manufacturing, Use and End of life). Therefore, the score assigned to the AM product life cycle ranges between 1 and 5. The score of 1 corresponds to the minimum possible score and is given by the sum of the minimum possible scores of the five life cycle stages (0,2+0,2+0,2+0,2+0,2=1). On the other hand, the score of 5 corresponds to the maximum possible score and is given by the sum of the maximum possible scores of the five life cycle stages (1+1+1+1+1=5).

3.8 Interpretation of the results

The interpretation of the results is the last step of the proposed methodology. It aims to classify the social impacts of the product according to the interpretation of the aggregated scores obtained. As explained in the previous section, the scores are aggregated at different levels of the assessments, which allows the identification of the social hotspots (negative social impacts) throughout the value chain of the product. By knowing which are the main hotspots in the assessment, the organizations can concentrate their efforts on these problems to find measures and solutions to improve the negative social impacts.

To interpret the meaning of the aggregated scores, cut-off scores were determined for each level of the assessment, to differentiate the positive from the negative social impacts. The cut-off score has been set as the mid score between the minimum and maximum possible scores for each level of the assessment, as shown in equation 3.9.

$$\text{Cut-off score} = \frac{\text{Minimum possible score} + \text{Maximum possible score}}{2} \qquad \text{(eq. 3.9)}$$

Above the cut-off score, the social impact is classified as positive, and below the cut-off score, the social impact is classified as negative. Furthermore, different scores bands were adopted to allow a more specific categorization of the social impacts. Specific details regarding the score interpretation will be presented for each level of the assessment in the next subsections.

3.8.1 Interpretation of the aggregated scores at stakeholder category and subcategory level

The results of the indicator calculation are first aggregated in the form of scores at subcategory level and then at the stakeholder category level, enabling the results of the indicators to be interpreted at these levels of the assessment. As described in section 3.7, the subcategories are assessed by a different number of indicators, which means that the subcategories will have different minimum, maximum and cut off scores, depending on the number of indicators considered. Analyzing Figure 3.6, it is possible to observe that the subcategory "Privacy" in the stakeholder "Consumer", comprising 2 indicators, has a minimum and maximum aggregated score of 0.0154 and 0.0769, respectively. Applying equation 3.9, the score of the subcategory is set as 0.04615, which means that if the subcategory aggregated score is above this value, the social impact is positive. However, if the subcategory aggregated score is under this value, the social impact is negative. The same rationale is applied to the interpretation of the stakeholder categories scores. The cut-offs scores allow us to identify hotspots within each life cycle stage with respect to the subcategories and stakeholders considered in the study. The subcategories and stakeholder categories that have scores below the cut-off scores are identified as hotspots that should be investigated. The organizations' main efforts should focus on these issues, and in trying to find solutions to improve the social impacts. This is very relevant in the case of the stakeholder categories because it allows identifying, within each life cycle, the stakeholders that are experiencing the most negative impact, and consequently, are being negatively affected by the social impacts of the product.

3.8.2 Interpretation of the aggregated scores at the life cycle stage level

As previously mentioned, all the five life cycle stages considered in the study are assigned a score between 0.2 and 1, which corresponds to the minimum and maximum possible score. The cut-off score is set as 0.6 since it is the mid score between 0.2 and 1 (Figure 3.6). That being said, if the score assigned to the life cycle stage is above the cut-off score, it means that the product has a positive social impact on the life cycle stage. On the other hand, if the life cycle stage score is below the cut-off score, it means that the product has a negative social impact on the life cycle stage.

Figure 3.7 shows the rating scale proposed to classify the social impacts within each life cycle stage. As shown, a color coding scheme is proposed for the categorization of social impacts. A score between 0.2 to 0.4 corresponds to a highly negative social impact, a score between 0.4 to 0.6 corresponds to a negative social impact, a score between 0.6 to 0.8 corresponds to a positive social impact, and finally, a score between 0.8 to 1 corresponds to a highly positive social impact. The life cycle stages with scores between 0.2 and 0.4 (highly negative social impact) and 0.4 and 0.6 (negative social impact) are identified as hotspots that should be further investigated. The organizations engaged in these life cycle stages must focus their efforts on finding alternatives and solutions to reduce their social impact.

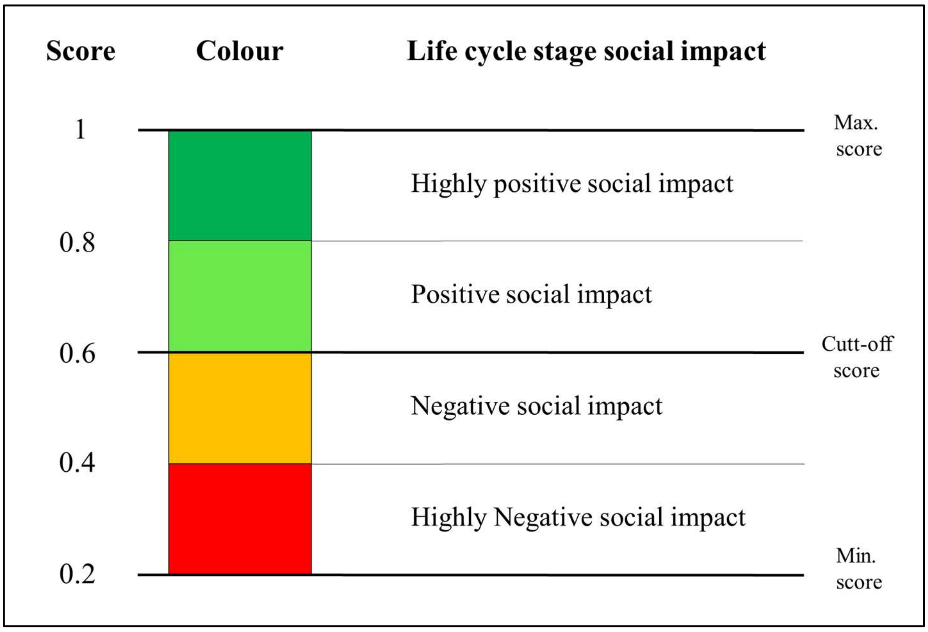


Figure 3.7 - Rating scale proposed to classify the social impacts of each life cycle stage

3.8.3 Interpretation of the final AM product life cycle score

The AM product final score corresponds to the sum of the five life cycle stages scores considered in the study, i.e., Product Design score, Raw materials production score, Manufacturing Score, Use score and End of life score. As previously stated, each of the five life cycle stages can be assigned a score between 0,2 and 1. Aggregating these values for all life cycle stages will result in the overall score of the AM product life cycle ranging between 1 to 5, where 1 corresponds to the minimum possible score and 5 to the maximum possible score of the AM product life cycle. The cut-off score for the AM product life cycle is set as 3 since it is the mid score between 1 and 5. From the overall life cycle perspective, the product has a negative social impact when the score of the product is below 3. On the contrary, the product has an overall positive social impact when assigned a score above 3.

The rating scale proposed for the overall social impact of the AM product life cycle is depicted in Figure 3.8**.** As shown, the social impact of the product is classified as a highly negative, negative, positive and highly positive, when assigned a score of 1 to 2, 2 to 3, 3 to 4, and 4 to 5, respectively.

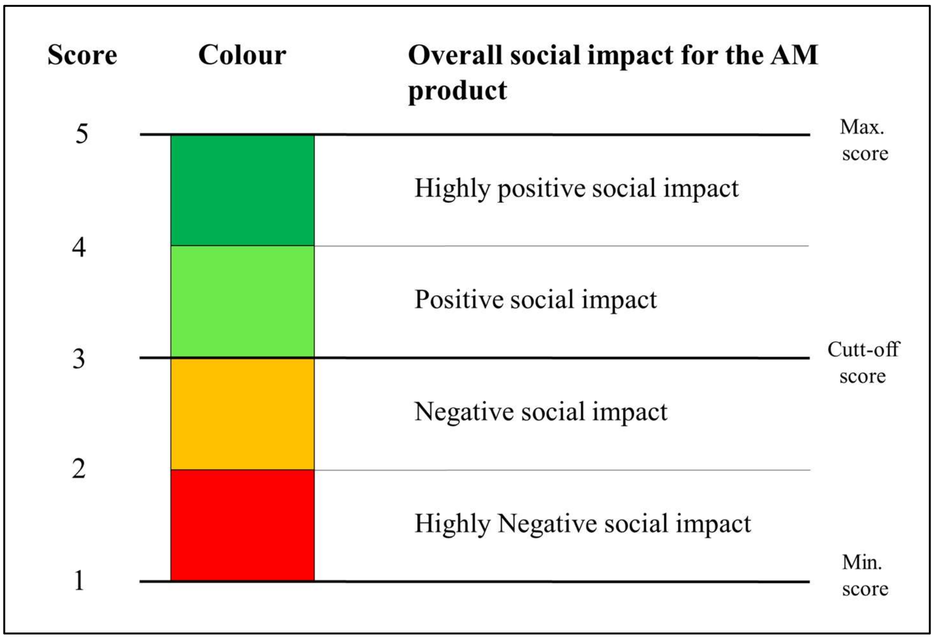


Figure 3.8 - Rating scale proposed to classify the overall social impact of the Additive Manufacturing product life cycle

3.9 Computational application model of the proposed SLCA methodology

To implement the proposed SLCA methodology, a computational application model was also developed in Excel for the present study. Several print shots of the model developed are displayed in Annex E. As shown in Table 3.9, the excel file of the model is divided into 4 groups of sheets, namely "Introduction to the model", "Data Collection", "Calculation of the Indicators scores", "Calculation of the Life cycle stages scores" and finally, "Calculation of the AM product final score". Each group of sheets is composed of a different set of sheets and are described in detail below.

Since the model has not yet been applied in any specific case study, random data were used as input to the model developed. That being said, the values and results visualized in this section and Annex E were obtained based on random data used by the author of this dissertation. The developed model can be made available, through a request to the author of this dissertation, until May 2019.

Introduction to the model

In the first phase of the model, an overview of the model components is presented. As shown in Table 3.9, this group of sheets is composed of the sheets *"SLCA methodology"*, "*AM Product Life Cycle"*, *"Stakeholders and subcategories"*, *"Indicators"* and *"Indicators Group"*. The goal is to provide information to the researchers regarding the characteristics of the model and how to use the model when conducting a case study.

Table 3.9 - Structure of the excel file of the model developed

Group of Sheets	Sheets	Description
Introduction to the model	*SLCA methodology* *AM Product Life Cycle* *Stakeholders and subcategories* *Indicators* *Groups of indicators*	It presents an overview of the SLCA methodology developed and provides information on how to apply the model when conducting a case study.
Data collection	*Data collection_Product Design* *Data collection_Raw Materials* *Data collection_Manufacturing* *Data collection_Use* *Data collection_End of Life*	The data required to measure the indicators for each life cycle stage are collected and inserted in these sheets.
Calculation of the indicators Scores	*Indicators score_Product Design* *Indicators score_Raw Materials* *Indicators score_ Manufacturing* *Indicators score_ Use* *Indicators score_ End of life*	The indicators scores are calculated for each life cycle stage, based on the data collected and inserted in the previous group of sheets.
Calculation of the Life Cycle Stages Score	*Product Design_SCORE* *Raw Materials_SCORE* *Manufacturing_SCORE* *Use_SCORE* *End of life_SCORE*	The indicators scores calculated in the previous group of sheets are aggregated within each life cycle stage, to obtain a single score, between 0,2 to 1, that corresponds to the life cycle stage score.
Calculation of the AM Product Final SCORE	*AM Product Life Cycle_SCORE*	In this sheet, the life cycle stages scores are summed up to obtain the overall score of the AM Product Life Cycle, between 1 and 5.

Data Collection

This group of sheets is composed of 5 sheets, one sheet for each of the five life cycles considered in the study. The researcher must enter the data collected to measure each indicator in the last column of these sheets. In Annex E.1, it is possible to visualize the Excel sheet *"Data Collection_Manufacturing"*, relative to the data collection process for measuring some indicators in the Manufacturing stage. As it is possible to see, the data and data types needed to measure each indicator presented are indicated, and the researcher only needs to enter the required data in the last column of the worksheet.

In each of the five sheets, it should also be indicated the reference period of the data and the organization where the data were collected. This procedure should be done in the data collection process data for each life cycle stage.

The data entered in each of the sheets of this group will be used as input to calculate the indicators scores in the next group of sheets.

Calculation of the Indicators Score

In the five sheets of this group, the indicators scores for each life cycle stage are calculated, based on the data inserted in the previous group of sheets. In each of the five sheets, the characteristics (description, stakeholder, subcategory, type, group of indicators and desired direction), the calculation method and the final score obtained for each indicator are presented. In Annex E.2, where a print shot of the sheet "*Indicator score_Manufacturing*" is displayed, it is possible to verify the calculation method for each of the four groups of indicators defined in this study.

Calculation of the Life Cycle Stages Score

In these sheets, the indicator scores are aggregated within each life cycle stage, to obtain a single final score, between 0.2 to 1, that corresponds to the life cycle stage score. In Annex E.3, it is possible to see all the steps of the aggregation method, through which the scores of the indicators are aggregated to obtain a final score of 0.7, which corresponds to the Manufacturing life cycle stage score. The score obtained corresponds to a "Positive Social Impact".

In order to obtain a more detailed perception and visualization of the social impacts within each life cycle stage of the AM product, the model includes the graphical representation, through bar graphs, of the scores of each stakeholder and subcategory. Thus, for each life cycles stage, a bar chart is provided where the scores of the stakeholders are represented, as well as the minimum and maximum score possible for each of them. Figure 3.9 shows the minimum, maximum and obtained scores of the stakeholder categories Worker, Local Community, Value Chain actors, Society, and Consumer, affected in the Manufacturing stage.

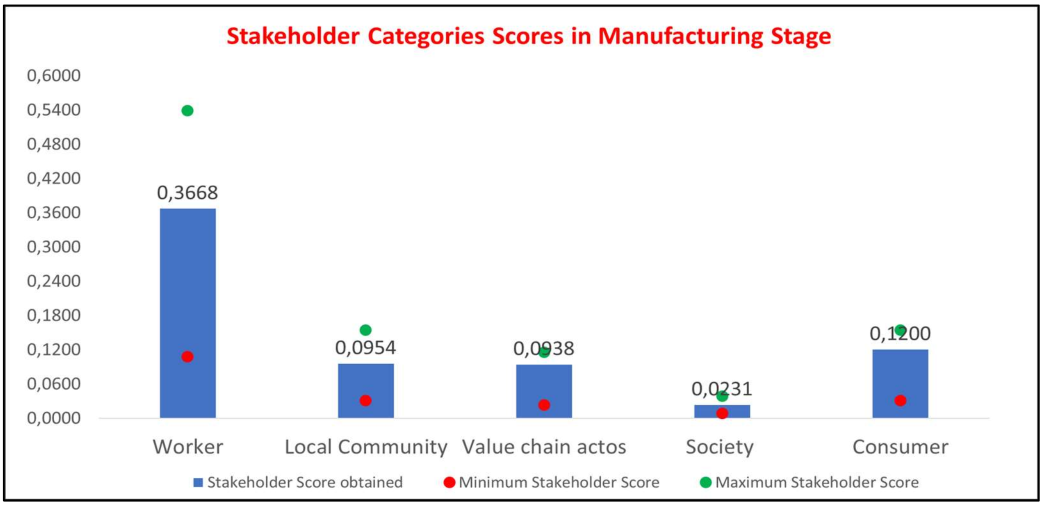


Figure 3.9 - Stakeholder Categories Scores in the Manufacturing Stage

For each stakeholder category, within each life cycle stage of the AM product, a bar chart is also provided which represents the scores for each subcategory, as well as its minimum and a maximum possible score. Figure 3.10 presents the results of the subcategories Health and safety, Equal opportunities, Psychological working conditions, Fair Salary, Working hours, Child labor and Social benefit/social security, for the stakeholder Worker, in the Manufacturing Stage.

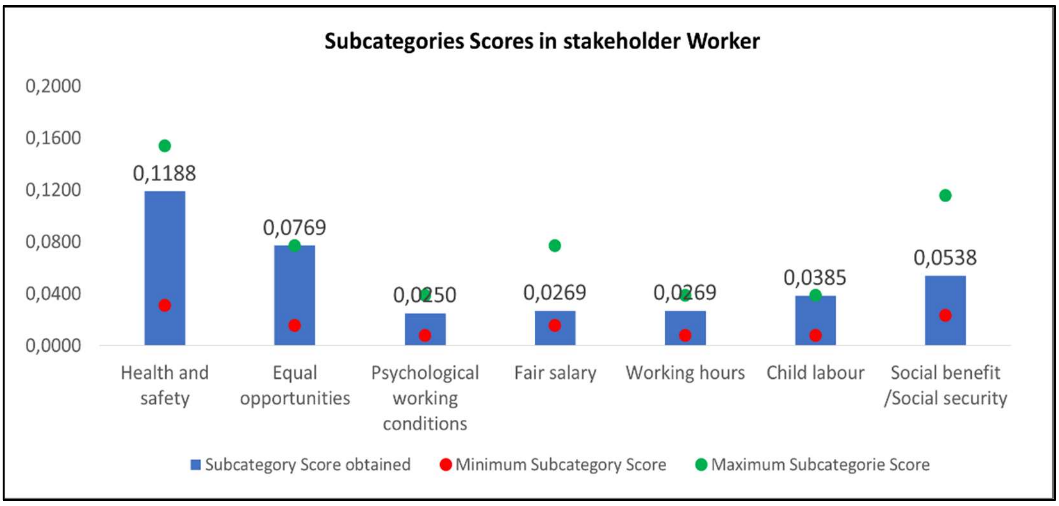


Figure 3.10 - Subcategories Scores for the stakeholder Worker, in the Manufacturing Stage

Calculation of the AM Product Final SCORE

In the last group of sheets, the five life cycle stages aggregated scores are summed up to obtain a final score, between 1 and 5, that corresponds to the overall score of the AM product Life Cycle. In Annex E.4, it is possible to observe the scores of the five life cycle stages of the AM product, namely the Product Design Score (0.70), the Raw Materials Productivity Score (0.68), the Manufacturing Score (0.70), the Use Score (0.59) and the End of Life Score (0.81). Adding these scores gives a score of 3.47 that corresponds to the overall score of the AM product Life Cycle. This score is above the cut off score (3) and represents an Overall Positive Social Impact. This means that, in general, the AM product has a positive social impact on its stakeholders throughout its complete life cycle.

In Annex E.4, it is also provided a graphical representation, through a bar graph, of the scores obtained for each of the five life cycle stages, as well as their minimum and maximum possible scores. As it can be seen, only the Use stage has a score (0.59) below the cut off score (0.6), representing a negative social impact in this life cycle, and consequently, a hotspot in the assessment. Therefore, organizations should concentrate their efforts on this life cycle stage to propose measures and solutions to improve the negative social impact.

Chapter 4: Exploratory case study

This chapter will be focused on the case study developed to validate the initial set of indicators proposed in the SLCA methodology presented in the previous chapter. Initially, the case study research methodology will be presented. The following sections will be designated to provide a brief description of the company where the study was conducted and to explain the data collection process used in the case study. In the end, the results of the questionnaire are presented and analyzed. Based on these results a final set of indicators is determined for the SLCA methodology proposed in this study.

4.1 Case study research methodology

Case studies allow researchers to investigate contemporary and complex phenomena within its real-life context through different sources of evidence (Voss, Tsikriktsis, & Frohlich, 2002). It can include data from direct observation, documents, artifacts, surveys, interviews or from public and private archive (Jennifer, 2002).

According to Eisenhardt (1989), the case study approach is most suited to the study of new research areas or research areas for which the existing theory is still inappropriate. This approach provides unique means to develop and test theory and has been widely used for this purpose in several scientific areas, such as psychology, sociology, political science, anthropology, history, economics, urban planning, public administration, public policy, management, social work, and education (Dubois & Gadde, 2002).

Conducting a case study can often be very time consuming and expensive. It requires skilled interviewers and great care is needed in generalizing the conclusions drawn from the results of a limited set of cases (Voss et al., 2002). Despite these obstacles, the results of case research can have a very high impact. Meredith (1998) highlights the main strengths of using case research:

- The phenomenon can be studied in its natural setting and meaningful, relevant theory generated from the understanding gained through observing actual practice.
- The case study research allows the questions of why, what and how, to be answered with a full understanding of the nature of the phenomenon being study.
- The case study research method is very useful in exploratory investigations where the phenomenon is not yet understood, and the variables are still unknown.

The research question and the state of knowledge related to the phenomenon being studied determine when a case study research approach is appropriate or even necessary (Stuart, Mccutcheon, Handfield, Mclachlin, & Samson, 2002). According to Voss et al. (2002), case studies can be used for different research purposes such as exploratory, theory building, theory testing, and theory testing/definition.

Table 4.1 describes each research purpose and links them with typical research questions, research structures, and data collection techniques.

The case study developed for the present study it is exploratory since it aims to validate the initial set of indicators proposed in the methodology developed in Chapter 3. The research purpose is to determine if these indicators capture/reflect the social impacts of AM technology.

The case study was conducted in a company specialized in the use of AM, based in Bristol, England. Secondary data was collected through the company's website to obtain a bigger picture of the type of process used by the company, its products, and customers. Primary data was collected through a questionnaire interview with an employee of the company. In this questionnaire, the respondent stated, according to his experience in the company, how AM technology affects each of the proposed indicators, more specifically whether it increases, decreases, or does not have any impact on them.

Based on the answers given by the respondent and the criteria defined by the author of this dissertation to validate the indicators, a final set of indicators was determined. These indicators capture the social impacts of AM technology and will be used in the methodology proposed.

Table 4.1 - Case study research purposes

Adapted from Handfield and Melnyk (1998) and Voss et al. (2002)

Research purpose	**Research question**	**Research structure**	**Data collection techniques**
Exploratory – Uncover areas for research and theory development	Is it interesting enough to justify research?	In-depth case studies Unfocused, longitudinal field study	Observation. Interviews, Documents
Theory building - Identify key variables, identify linkages between variables and why these relationships exist	What are the key variables? What are the patterns or linkages between variables? Why should these relationships exist?	Focused case studies In-depth field studies Multi-site case studies Best-in-class cases Focused	Observation, In-depth interviews, Diaries, Survey questionnaires, Unobtrusive measures
Theory validation - Test the developed theories and predict future outcomes.	Are the theories we have generated able to survive the test of empirical data? Did we get the behavior that was predicted by the theory or did we observe another unanticipated behavior?	Experiment Quasi-experiment Multiple case studies Large-scale sample of population	Structured Interviews, Documents, Open and closed ended questionnaires, Lab experiments. Field experiments, Quasi-experiments, Surveys
Theory extension/refinement - To better structure the theories in light of the observed results	How applicable/generalizable are the developed theories? Where do the theories apply?	Experiment Quasi-experiment Large-scale sample of population Contextual case studies	Structured, Interviews, Documents, Open and closed ended questionnaires, Lab experiments, Field experiments, Quasi-experiments, Surveys, Documentation, Archival Research

4.2 Company characterization

The company was founded in 2012 by two employees, and its initial goal was to use the AM technology in the production of compact heat exchangers. The main focus of the company continues to be the production of heat exchangers, both high temperatures and low temperatures. However, the company also produces products in the areas of:

- Turbo machinery such as lightweight and cooled turbine wheels.
- Combustion and Fuel delivery parts, including injectors and combustor cans.
- Integrated systems such as waste heat recovery system.

The AM technique used by the company is the Selective Laser Melting (SLM). The company currently has 8 machines (3D printers) that work with this type of technology. In SLM, a 3D CAD model of the product is first generated. From here the model is sliced into very tiny 2D layers which, when added together, make up the product design. For each slice of CAD data, a very thin layer of metal powder is deposited over a building platform in the machine. Then, the selected areas of the metal powder are precisely melted by a high-power laser beam, producing the contour of the component according to the 3D model data. The building platform is then lowered, the next layer of metal powder is deposited on top and melted again. This process is repeated building up, layer by layer until the final component is complete. In the end, the finished component is cleaned of any excess powder, the necessary support structures are removed, and the component is reworked if necessary.

The use of AM technology in the manufacturing process allows its products to be smaller, lighter and more resilient than those that are available in the market. These characteristics dramatically increase the performance and efficiency of the products, which allows its customers the reduction of costs and lead times and materials savings. Its main costumers are in the automotive sector. However, due to the unique characteristics of its products, the company recently entered in other markets such as aerospace, defense, energy generation, and motorsports.

In the last years, the company has been continuously growing and currently has around 50 employees, most of whom are expert engineers qualified with PhD or Masters level degrees. In 2017, its turnover was about 1 million pounds, and the goal is to increase this value in the coming years. To this end, the company intends to continue investing in new machinery and research in order to increase its production capacity without compromising the level of quality associated with its products.

4.3 Data collection and analysis

In this case study, both primary and secondary data were used. The secondary data was collected through the company's website and provided detailed information about the company's structure, as well as its main products and processes. For the collection of primary data, a structured interview questionnaire, presented in Annex F, was developed considering the initial set of indicators presented in Table 3.2. The respondent is an engineer working in the area of quality and inspection and has been in the company for about two years. Despite having only two years of experience, he is one of the company's oldest employees, since the company is relatively new (founded in 2012) and started with very few employees.

The goal of the questionnaire is to capture how AM technology affects each of the indicators initially proposed, more specifically whether it increases, decreases, or does not have any impact. The responses were provided according to the respondent's perception of the AM technology's effects on the social performance of the organization.

In order to determine which indicators would be selected or removed from the initial list of indicators shown in Table 3.2, the following criteria were defined:

- The indicators which the respondent considered that the AM technology increases or decreases, were selected since they capture/reflect the social impacts of the AM technology.
- On the other hand, the indicators which the respondent considered that AM technology has no impact on, were excluded, since they are not relevant within the social context of AM technology.
- The indicators that the respondent was not able to identify the impact of AM technology were also selected for the study. These indicators should be validated in future research on the topic.

The results of the questionnaire are presented in Table 4.2. The answers ("Increase", "Decrease", "No Impact") are given according to the respondent's perception of the effects of AM technology on the social performance of the organization. For some indicators, the respondent was not able to identify the impact of AM technology so in these cases, the phrase "Do not know" is displayed in the responses column. Supporting evidence for his answers are also given. In this way, it is identified whether AM technology has a positive or negative impact on the indicator.

As shown in Table 4.2, the respondent identified that AM technology increases the values of the following indicators:

- "Preventive measures and emergency protocols regarding accidents and injuries"
- "Use of personal protective equipment"
- "Average monthly basic remuneration of employees"
- "Average weekly hours of work by full-time employee"
- "Percentage of workers educated by the organization regarding AM technology
- "Percentage of qualified workers in the organization "
- "Percentage of spending on locally-based suppliers"
- "Percentage of local suppliers"

- “Integration of ethical, social and environmental criteria in purchasing and distribution policy”
- “Organization’s policy and practice regarding the protection of intellectual properties rights”
- “Organization's efforts and measures to ensure the protection of consumer privacy”

On the other hand, the respondent stated that the AM technology decreases the values of the following indicators:

- “Non-Fatal occupational accidents incidence rate”
- “Fatal occupational accidents incidence rate”
- “Percentage of employees receiving minimum wage”
- “Presence of child labor in the organization”
- “Percentage of the workforce hired locally”
- “Percentage of the consumers affected by situations of breach of privacy or loss of data”

All the 17 indicators mentioned above will be selected because they negatively or positively capture/reflect the social impacts of AM technology.

The indicators on which the respondent identified that AM technology has no impact are as follow:

- “Presence of female employees in management positions” - There are only two female employees in management positions. The respondent explained that this company is mostly made up of male employees, just like the majority of engineering companies in England.
- “Gender pay gap” - There are evidences of a Gender pay gap in the organization. However, this gap is not due to AM technology, but rather to the socioeconomic context of England, where men traditionally receive higher wages than women, especially in managerial positions.
- "Organization's efforts in promoting AM education initiatives in the local community" - To date, the company has not carried out any training or promotion of the use of AM technology in the local community.
- “Payment on time to the suppliers” - The respondent explained that there have never been any delays in payment to suppliers.
- “Percentage of consumers negatively affected regarding their health and safety” - The respondent stated that they have never received any complaints from their consumers.
- “Organization's efforts and measures to protect consumer health and safety” – To date, there are no defined measures and policies in the company to protect the consumer health and safety.

The six indicators described above will be excluded from the study since they are not relevant within the social context of AM technology.

Lastly, the respondent was not able to identify the social impact of AM technology in three indicators, namely the indicators “Employee work satisfaction”, “Access to legal social benefits according to the

Table 4.2 - Results of the questionnaire

Social theme	N	Indicator	Results		Comment / Justification
			Response	impact	
Health and safety	1	Non-Fatal occupational accidents incidence rate	Decreases	Positive	The only accidents reported so far are minor cuts on the skin of the technicians working with the printers. These accidents occur in the post-production phase and the removal of the support structures used in the process.
	2	Fatal occupational accidents incidence rate	Decreases	Positive	There has been no occurrence so far.
	3	Use of personal protective equipment (PPE)	Increases	Positive	To reduce the high risk of inhalation of the metal powder used in the process, the technicians that work with the printers use appropriate PPE.
	4	Preventive measures and emergency protocols regarding accidents and injuries	Increases	Positive	There are strict measures due to the danger associated with the inhalation of the metal powder used in the process. Since this powder is composed of millions of particles with dimensions ranging between 15 to 45 microns (μ), there is a high risk of inhalation of these particles that in the long term can cause several respiratory diseases. In order to reduce this risk, the technicians that work with the printers use appropriate Personal Protective Equipments (PPE's).
Equal opportunities/ Discrimination	5	Presence of female employees in management positions	No impact	—	As is the case of most engineering companies in England, this company is mostly made up of male employees. The company has 9 female employees, of which only 2 hold management positions, one in the customer validation department and the other in the human resources department.
	6	Gender pay gap	No impact	—	There is a gender pay gap in the company. However, this wage gap is not due to the social impact of AM technology, but rather to the social context of the country in which the company is based. In England, men traditionally receive higher wages than women, especially in managerial positions.
Fair salary	7	Average monthly basic remuneration of employees	Increases	Positive	Since most of the employees are qualified with masters and doctoral degrees in their respective areas, the average salary of the company is relatively high.
	8	Percentage of employees receiving minimum wages	Decreases	Positive	There is no employee receiving the minimum wage at the company.
Physiological Working conditions	9	Employee work satisfaction	Do not know	—	
Working hours	10	Average weekly hours of work by full-time employee	Increases	Negative	As the company works with AM technology, which is a relatively new technology, most of the company's engineers need to be constantly studying and being aware of the new advances in AM technology that are constantly occurring. For these reasons, engineers often take much work to home and work more hours than the 40 weekly hours defined by law.
Child labor	11	Presence of child labor in the organization	Decreases	Positive	There is no employee under the age of 15 in the company.
Social benefit/Social security	12	Access to legal social benefits	Do not know	—	
	13	Percentage of workers educated by the organization regarding AM technology	Increases	Positive	The training of most employees is mainly about hygiene and safety at work. The technicians are trained externally in Renishaw, the company that produces the machines, in how to operate the machines, the individual care that they must have when using the machines and the importance of the use of PPE's.

Table 4.1 - Results of the questionnaire (cont.)

Social theme	Nº	Indicator	Results		Comment / Justification
			Response	impact	
Social benefit/Social security	14	Percentage of qualified workers in the organization	Increases	**Positive**	Of the 50 employees of the company, only the 4 technicians who operate the machines are not qualified. They are responsible for feeding/cleaning the machine and for removing the metal powder and support structures used in the process.
Local employment	15	Percentage of the workforce hired locally	Decreases	**Negative**	To work with AM technology, it is necessary to have qualified people, both the engineers and the technicians who operate the machines. The probability of having people with these qualifications in the locality where the company is settled is very small. Currently, most of its workers come from different parts of England, who have come to live near the locality (Bristol) where the company is established. The company also has 7 foreign employees that came from different parts of Europe.
	16	Percentage of spending on locally-based suppliers	Increases	**Positive**	The three main suppliers are all located within a 60-kilometer radius of the company's headquarters.
	17	Percentage of local suppliers	Increases	**Positive**	The company has three main suppliers. The supplier who provides the machines (Renishaw) and some of the metal powders used in the process. The supplier who exclusively provides the metal powders used in the process and a supplier (local workshop) who provides the plates used to relieve the mechanical stresses resulting from the thermal stresses of the SLM process. The three suppliers are all located within a 60-kilometer radius of the company's headquarters.
Access to immaterial resources	18	Organization's efforts in promoting AM education initiatives in the local community	No impact	—	To date, the company has not carried out any training or promotion of the use of AM technology in the local community where they are settled.
Promoting social responsibility	19	Integration of ethical, social and environmental criteria in purchasing and distribution policy	Increases	**Positive**	It is part of the company's policy and philosophy.
Respect of intellectual property rights	20	Organization's policy and practice regarding the protection of intellectual properties rights	Increases	**Positive**	The protection of intellectual property rights is an important matter in companies working with AM technology.
Supplier Relationships	21	Payments on time to suppliers	No impact	—	There have never been any delays in payment to suppliers.
Prevention and Mitigation of Conflicts	22	Organization's efforts to prevent the manufacturing of armed conflicts weapons using AM	Do not know	—	The respondent did not know if there are policies and measures relating to this topic, however, pointed out that the company produces several products for the defense sector of England.
Consumer's health and safety	23	Percentage of consumers negatively affected regarding their health and safety	No impact	—	They have never received any complaints regarding cases where the consumer's health and safety have been jeopardized by the use of their products.
	24	Organization's efforts and measures to protect consumer health and safety	No impact	—	There are no defined measures and policies to protect consumer health and safety.
Consumer's privacy	25	Percentage of the consumers affected by situations of breach of privacy or loss of data	Decreases	**Positive**	They have never received any complaints from consumers affected by situations of breach of privacy or loss of data.
	26	Organization's efforts and measures to ensure the protection of consumer privacy	Increases	**Positive**	There are quite strict measures. The issue of confidentiality is very important in the company because of the type of clients they work with.

country laws" and "Organization's efforts to prevent the manufacturing of armed conflicts weapons using AM". According to the criteria previously defined, although the respondent has not been able to identify the AM technology impact, these indicators will also be selected for the study.

Thus, of the 26 indicators initially proposed in the methodology developed in Chapter 3, 20 indicators were selected, and 6 indicators were excluded. Based on the responses given by the respondent, it was also possible to determine the type of impact of AM technology, i.e., whether it has a positive impact or a negative impact. As shown in Table 4.2, of the 17 indicators from which the respondent was able to identify whether the AM technology increased or decreased the values of the indicators, it was possible to determine that the AM technology had a positive impact on 15 indicators. On the other hand, it was also identified that the technology had a negative impact on 2 indicators, namely the indicators "Average weekly hours of work by full-time employee" and "Percentage of the workforce hired locally".

Table 4.3 shows the final set of indicators, comprised of 20 indicators, that were selected based on the results of the case study. These indicators will be used in the SLCA methodology proposed in Chapter 3 to assess the social impacts of AM products.

Table 4.3 - Final set of indicators selected according to the results of the exploratory case study

Stakeholder	Subcategory	Nº	Indicator
Worker	Health and Safety	1	Non-Fatal occupational accidents incidence rate
		2	Fatal occupational accidents incidence rate
		3	Use of personal protective equipment
		4	Preventive measures and emergency protocols regarding accidents and injuries
	Fair salary	5	Average monthly basic remuneration of employees
		6	Percentage of employees receiving minimum wages
	Working Conditions	7	Employee work satisfaction
	Working hours	8	Average weekly hours of work by full-time employee
	Child labor	9	Presence of Child Labour in the organization
	Social benefit/Social security	10	Access to legal social benefits according to the country laws
		11	Percentage of workers educated by the organization regarding AM technology
		12	Percentage of qualified workers in the organization
Local community	Local employment	13	Percentage of the workforce hired locally
		14	Percentage of spending on locally-based suppliers
		15	Percentage of local suppliers
Value Chain actors	Promoting social responsibility	16	Integration of ethical, social and environmental criterions in purchasing and distribution policy
	Respect of Intellectual Property Rights	17	Organization's policy and practice regarding the protection of intellectual properties rights
Society	Prevent and Mitigation of Conflicts	18	Organization's efforts to prevent the manufacturing of armed conflicts weapons using AM
Consumer	Privacy	19	Percentage of the consumers affected by situations of breach of privacy or loss of data
		20	Organization's efforts and measures to ensure the protection of consumer privacy

Chapter 5: Conclusions and final considerations

The fifth and final chapter of this dissertation provides an overview of the study, as well as its main conclusions and contributions. It also identifies the research implications, main challenges and limitations of the study and provides recommendations for future work.

5.1 Conclusions

The present dissertation had the objective to develop an SLCA based methodology to assess the social impacts of AM products. In order to do that, it was necessary to identify metrics and indicators to measure the social impacts. Moreover, it was also intended to validate the proposed indicators, through an exploratory case study.

The proposed methodology is composed of 6 steps and was developed to assess the social impacts of AM products, from a life cycle perspective. A conception to grave approach was adopted, which allowed studying the social impacts in five life cycle stages of the AM product: (1) Product Design stage; (2) Raw materials production stage; (3) Manufacturing stage; (4) Use stage and (5) End of life. At each considered life cycle stage, different people, entities or organizations are affected by the social impacts. Therefore, it was necessary to define which stakeholders would be affected by the social impacts of the AM product. The UNEP/SETAC (2009) guidelines identify stakeholder categories that are involved in different stages of the product life cycle stage. The stakeholder categories used in this methodology are the ones proposed in these guidelines. They are presented in five categories: Worker, Local community, Value chain actors, Society, and Consumer. Each stakeholder category is classified according to subcategories, i.e., socially significant issues of interest to stakeholders, to better identify in which contexts these stakeholders can be affected. The author of this dissertation selected 15 subcategories from the UNEP/SETAC (2009) guidelines, 7 related to the Worker, 2 to the Local community, 3 to the Value chain actors, 1 to the Society and 2 to the Consumer.

The SLCA methodology implies the use of indicators to measure the social impacts of products. These indicators can be quantitative, semi-quantitative, or qualitative. Moreover, all indicators have a desired direction for sustainability, that can be either positive or negative, depending on the nature of the social impact. For example, a positive social impact will have a positive desired direction for sustainability, which means that the objective is to increase the value of these indicators. The same logic applies to the negative social impacts, that have a negative desired direction for sustainability.

From the body of literature, a total of 26 potential indicators to assess the social impacts of AM products were identified for the five stakeholder categories, 14 are relative to the Worker, 4 to the Local community, 3 to the Value chain actors, 1 to the Society and 4 to the Consumer. A higher number of indicators was identified for the stakeholder Worker. This category is the most addressed in SLCA studies which means that the Worker is the most impacted stakeholder category from a social point of view. On the other hand, only 1 indicator was identified for the stakeholder Society. There is a lack of information regarding this category in SLCA literature, and very few indicators have been proposed to assess this category. Most of the indicators were screened from the work of Ribeiro (2017), while others were selected from the Methodological sheets (UNEP/SETAC, 2013) and several SLCA case studies.

After selecting the stakeholders, subcategories and indicators, it was necessary to determine how the indicators would be calculated and aggregated to obtain a final score that corresponded to the social impact of the product. The methods proposed by the authors of the SLCA studies described in Section 2.2.6 were used and adapted to develop specific topics of the methodology such as the calculation of the indicators, the scoring system, the aggregation of the indicators scores and the interpretation of the scores.

The last goal of this dissertation was to validate the 26 potential indicators initially proposed to assess the social impacts of AM products. The goal was to understand if these indicators really captured the social impacts of AM technology. For that purpose, an exploratory case study was conducted in an AM company based in Bristol, England. The results of the case study revealed that 6 of the 26 indicators initially proposed did not capture the social impacts of AM and as such were removed from the methodology. They are as follows: "Presence of women in management positions", "Gender pay gap", "Organization's efforts to promote AM education initiatives in the local community", “Payments on time to suppliers”, "Percentage of consumers negatively affected in relation to their health and safety" and "Organization's efforts to protect consumer health and safety". Thus, through the case study, 20 indicators have been validated to assess the social impacts of AM and therefore were used in the methodology developed in this dissertation.

To support the implementation of the proposed SLCA methodology, a computational application model was also developed for the present study. With this model, it is possible to apply the methodology in a case study to study the social impact of AM products. When entering the data necessary to measure the indicators in each life cycle stage, the model calculates the indicators scores, the life cycle stages scores and finally, the overall score of the AM product life cycle. Annex E provides an overview of the excel file on which the model was developed.

5.2 Research implications

As of the date of this research, there is still very few work done regarding the social impacts of AM technology, and this research is intended to be a first step in the development of this area of study. The proposed methodology can be perceived as a first attempt to measure the social impacts of a product produced by AM technology from a life cycle perspective. The methodology still needs further validation from specialists in this field, so it could be applied in case studies to understand and validate its feasibility. With the application of the proposed methodology in a case study, it will be possible to identify the positive and negative social impacts associated with an AM product. The scoring system of the proposed methodology at different levels of assessment allows the identification of negative social impacts throughout the value chain of a product produced using AM technology. The organizations engaged in the value chain must focus their efforts on finding alternatives and solutions to reduce these negative social impacts. The cut-off scores provided by the methodology, allow the identification of hotspots within each life cycle stage with respect to the subcategories and stakeholders. By knowing what the main hotspots are, the organizations can concentrate their efforts on these problems to find measures and solutions. Furthermore, it will be possible to understand which stakeholders will be most affected by the social impacts of the product and which life cycle stages of the AM product will have the worst social performance.

5.3 Limitations

Due to the pilot nature of this study, regarding the AM technology and its social impacts, a group of limitations were found during the course of this research. The limitations are:

- The indicators initially proposed were validated based on only one exploratory case study. They were not discussed and validated by specialists in AM technology and social science, so it is possible that more reliable indicators may exist.
- The results of the case study are valid only for the context of the AM process studied in the company which is the SLM. The results cannot be generalized to other types of AM processes, since they may have different social impacts.
- The stakeholders addressed in the methodology were the ones provided in the Guidelines for Social Life Cycle Assessment of products. It is possible that more stakeholders can be affected by the social impacts of an AM product.
- The methodology still needs further validation from specialists in this field, so it could be applied in case studies to clarify and validate its feasibility.

5.4 Future Work

The methodology proposed in this dissertation, as previously mentioned, is expected to support and provide solid ground for future work in the research project FIBR3D. The proposals for future work on this project are:

- Validating the applicability of the methodology, through a case study in an additive manufacturing company, where it is possible to collect the necessary data to measure all the proposed indicators.
- It is expected that the social impacts may be different for each type of AM process that uses the technology, so it is also recommended to validate the methodology with other types of AM processes and products.
- Assigning different weights to the indicators, stakeholders and life cycle stages, according to their relevance in the context of AM, using, for example, fuzzy logic.
- Exploring in detail which stakeholders are affected in each life cycle stage of the AM product. For example, in the use stage, the "Consumer" should be the only stakeholder considered, since it is the only stakeholder that interacts with the product in this life cycle stage.
- Including other possible stakeholder categories and subcategories, according to their relevance to the AM technology social impacts, in the methodology.
- Exploring more indicators for stakeholders, especially the stakeholder Society.
- Apply the methodology simultaneously with the E-LCA and LCC methodologies in a specific product made by AM technology. This way, it is possible to investigate and measure the social, environmental and economic impacts of the AM product.
- Exploring other AM social impacts and their connections with stakeholders and their respective subcategories and using them in the methodology.

References

Al-Meslemi, Y., Anwer, N., & Mathieu, L. (2018). Environmental Performance and Key Characteristics in Additive Manufacturing: A Literature Review. *Procedia CIRP, Proceedings - CIRP LCE 2018: The 25th CIRP Life Cycle Engineering (LCE) Conference, Copenhagen, Denmark*, *69*, 148–153. https://doi.org/10.1016/j.procir.2017.11.141

Alhamed, H., & Qiu, X. (2007). *A Model for Assessing Cost Effectiveness of Applying Lean Tools - A case study* (Master's thesis, Växjö University). Retrieved from http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A205422&dswid=8136

Aparcana, S., & Salhofer, S. (2013a). Application of a methodology for the social life cycle assessment of recycling systems in low income countries: Three Peruvian case studies. *International Journal of Life Cycle Assessment*, *18*(5), 1116–1128. https://doi.org/10.1007/s11367-013-0559-3

Aparcana, S., & Salhofer, S. (2013b). Development of a social impact assessment methodology for recycling systems in low-income countries. *International Journal of Life Cycle Assessment*, *18*(5), 1106–1115. https://doi.org/10.1007/s11367-013-0546-8

Arcese, G., Lucchetti, M. C., & Massa, I. (2017). Modeling Social Life Cycle Assessment framework for the Italian wine sector. *Journal of Cleaner Production*, *140*, 1027–1036. https://doi.org/10.1016/j.jclepro.2016.06.137

Arcese, G., Lucchetti, M. C., Massa, I., & Valente, C. (2018). State of the art in S-LCA: integrating literature review and automatic text analysis. *International Journal of Life Cycle Assessment*, *23*(3), 394–405. https://doi.org/10.1007/s11367-016-1082-0

Arcese, G., Lucchetti, M., & Merli, R. (2013). Social Life Cycle Assessment as a Management Tool: Methodology for Application in Tourism. *Sustainability*, *5*(8), 3275–3287. https://doi.org/10.3390/su5083275

ASTM International. (2013). *F2792-12a - Standard Terminology for Additive Manufacturing Technologies*. *American Society for Testing and Materials*. https://doi.org/10.1520/F2792-12A.2

Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, *60*(5), 677–688. https://doi.org/10.1016/j.bushor.2017.05.011

Benoit, C., Cavan, D. A., & Norris, G. (2012). Identifying social impacts in product supply chains: Overview and application of the social hotspot database. *Sustainability*, *4*(9), 1946–1965. https://doi.org/10.3390/su4091946

Benoît, C., Norrs, G. A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., … Beck, T. (2010). The guidelines for social life cycle assessment of products: Just in time! *International Journal of Life Cycle Assessment*, *15*(2), 156–163. https://doi.org/10.1007/s11367-009-0147-8

Bork, C. A. S., De Barba Junior, D. J., & De Oliveira Gomes, J. (2015). Social life cycle assessment of three companies of the furniture sector. *Procedia CIRP*, *29*, 150–155. https://doi.org/10.1016/j.procir.2015.02.191

Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrímsson, J. G., & Thiede, S. (2015). Direct digital manufacturing: Definition, evolution, and sustainability implications. *Journal of Cleaner Production*, *107*, 1–11. https://doi.org/10.1016/j.jclepro.2015.05.009

Ciroth, A., & Eisfeldt, F. (2016). PSILCA – A Product Social Impact Life Cycle Assessment database. Database version 1.0. Documentation, (March), 1–99. Retrieved from http://www.openlca.org/documents/14826/6d439d91-ddf5-480f-9155-e4787eaa0b6b

Ciroth, A., & Franze, J. (2011). *LCA of an Ecolabeled Notebook: Consideration of Social and*

Environmental Impacts Along the Entire Life Cycle. (GreenDeltaTC GmbH, Ed.). Berlin.

Di Cesare, S., Silveri, F., Sala, S., & Petti, L. (2018). Positive impacts in social life cycle assessment: state of the art and the way forward. *International Journal of Life Cycle Assessment*, *23*, 406–421. https://doi.org/10.1007/s11367-016-1169-7

Dreyer, L. C., Hauschild, M. Z., & Schierbeck, J. (2010). Characterisation of social impacts in LCA: Part 1: Development of indicators for labour rights. *International Journal of Life Cycle Assessment*, *15*(3), 247–259. https://doi.org/10.1007/s11367-009-0148-7

Dreyer, L., Hauschild, M., & Schierbeck, J. (2006). A Framework for Social Life Cycle Impact Assessment. *The International Journal of Life Cycle Assessment*, *11*(2), 88–97. https://doi.org/10.1065/lca2005.08.223

Dubois, A., & Gadde, L. E. (2002). Systematic combining: An abductive approach to case research. *Journal of Business Research*, *55*(7), 553–560. https://doi.org/10.1016/S0148-2963(00)00195-8

Eisenhardt, K. M. (1989). Building Theories from Case Research. *The Academy of Management Review*, *14*(4), 532–550. https://doi.org/10.5465/AMR.1989.4308385

Ekener-Petersen, E., & Finnveden, G. (2013). Potential hotspots identified by social LCA - Part 1: A case study of a laptop computer. *International Journal of Life Cycle Assessment*, *18*(1), 127–143. https://doi.org/10.1007/s11367-012-0442-7

Eurostat. (2013). *European Statistics on Accidents at Work (ESAW) - Summary methodology. Methodologies & Working papers*. https://doi.org/10.2785/40882

Falque, A., Feschet, P., Garrabé, M., Gillet, C., Loeillet, D., Lagarde, V., & Macombe, C. (2013). *Social LCAs. Socio-economic effects in value chains* (Fruitrop Thema). Retrieved from http://www.fruitrop.com/en/media/Publications/FruiTrop-Thema/Social-LCA-volume-1

Fava, J., Consoli, F., Denson, R., Dickson, K., Mohin, T., & Vigon, B. (1993). *A Conceptual Framework for Life-Cycle Impact Assessment*. (Society for Environmental Toxicology and Chemistry and SETAC Foundation for Environmental Education, Ed.). Pensacola, FL.

Fontes, J. (2014). Handbook for product social impact assessment.

Foolmaun, R. K., & Ramjeeawon, T. (2013). Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius. *International Journal of Life Cycle Assessment*, *18*(1), 155–171. https://doi.org/10.1007/s11367-012-0447-2

Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production*, *137*, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Franze, J., & Ciroth, A. (2011). A comparison of cut roses from Ecuador and the Netherlands. *International Journal of Life Cycle Assessment*, *16*(4), 366–379. https://doi.org/10.1007/s11367-011-0266-x

Gaasbeek, A., & Meijer, E. (2013). *Development and application of a standardized methodology for the PROspective SUstaInability assessment of TEchnologies. PROSUITE*. Retrieved from http://www.prosuite.org/c/document_library/get_file?uuid=31404a5b-b716-4a65-8d4e-1ac991a6dd79&groupId=12772

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., … Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *CAD Computer Aided Design*, *69*, 65–89. https://doi.org/10.1016/j.cad.2015.04.001

Garetti, M., & Taisch, M. (2012). Sustainable manufacturing: trends and research challenges. *Production Planning & Control: The Management of Operations*, *23*(2–3), 83–104.

Gauthier, C. (2005). Measuring corporate social and environmental performance: The extended life-cycle assessment. *Journal of Business Ethics*, *59*(1), 199–206. https://doi.org/10.1007/s10551-005-3416-x

Hosseinijou, S. A., Mansour, S., & Shirazi, M. A. (2014). Social life cycle assessment for material selection: A case study of building materials. *International Journal of Life Cycle Assessment*, *19*(3), 620–645. https://doi.org/10.1007/s11367-013-0658-1

Huang, S. H., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive manufacturing and its societal impact: A literature review. *International Journal of Advanced Manufacturing Technology*, *67*(5–8), 1191–1203. https://doi.org/10.1007/s00170-012-4558-5

Jennifer, R. (2002). Using case studies in research. *Management Research News*, *25*(1), 16–27. https://doi.org/10.1108/01409170210782990

Jiang, R., Kleer, R., & Piller, F. T. (2017). Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030. *Technological Forecasting and Social Change*, *117*, 84–97. https://doi.org/10.1016/j.techfore.2017.01.006

Jolliet, O., Müller-Wenk, R., Bare, J., Brent, A., Goedkoop, M., Heijungs, R., … Weidema, B. (2004). The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. *International Journal of Life Cycle Assessment*, *9*(6), 394–404. https://doi.org/10.1065/lca2004.09.175

Jørgensen, A. (2010). *Developing the Social Life Cycle Assessment: addressing issues of validity and usability (Doctoral dissertation, Technical University of Denmark)*. Retrieved from http://orbit.dtu.dk/en/publications/developing-the-social-life-cycle-assessment(39ef2db6-ef9b-42d5-87da-fd9bdfd45365).html

Jørgensen, A., Le Bocq, A., Nazarkina, L., & Hauschild, M. (2008). Methodologies for social life cycle assessment. *International Journal of Life Cycle Assessment*, *13*(2), 96–103. https://doi.org/10.1065/lca2007.11.367

Kafara, M., Süchting, M., Kemnitzer, J., Westermann, H. H., & Steinhilper, R. (2017). Comparative Life Cycle Assessment of Conventional and Additive Manufacturing in Mold Core Making for CFRP Production. *Procedia Manufacturing, Proceedings - GCSM 2014: The 4th Global Conference on Sustainable Manufacturing, Stellenbosch, South Africa*, *8*, 223–230. https://doi.org/10.1016/j.promfg.2017.02.028

Kellens, K., Mertens, R., Paraskevas, D., Dewulf, W., & Duflou, J. R. (2017). Environmental Impact of Additive Manufacturing Processes: Does AM Contribute to a More Sustainable Way of Part Manufacturing? *Procedia CIRP, Proceedings - CIRP LCE 2018: The 24th CIRP Conference on Life Cycle Engineering Environmental Conference*, *61*, 582–587. https://doi.org/10.1016/j.procir.2016.11.153

Khajavi, S. H., Partanen, J., & Holmström, J. (2014). Additive manufacturing in the spare parts supply chain. *Computers in Industry*, *65*(1), 50–63. https://doi.org/10.1016/j.compind.2013.07.008

Klopffer, W. (2003). Life-cycle based methods for sustainable product development. *International Journal of Life Cycle Assessment*, *8*(3), 157–159. https://doi.org/10.1007/BF02978462

Kovács, G., & Spens, K. M. (2005). Abductive reasoning in logistics research. *International Journal of Physical Distribution and Logistics Management*, *35*(2), 132–144. https://doi.org/10.1108/09600030510590318

Kruse, S. A., Flysjö, A., Kasperczyk, N., & Scholz, A. J. (2009). Socioeconomic indicators as a complement to life cycle assessment - An application to salmon production systems. *International Journal of Life Cycle Assessment*, *14*(1), 8–18. https://doi.org/10.1007/s11367-008-0040-x

Kruth, J. P., Leu, M. C., & Nakagawa, T. (1998). Progress in additive manufacturing and rapid prototyping. *CIRP Annals - Manufacturing Technology*, *47*(2), 525–540.

https://doi.org/10.1016/S0007-8506(07)63240-5

Kühnen, M., & Hahn, R. (2017). Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience. *Journal of Industrial Ecology*, *21*(6), 1547–1565. https://doi.org/10.1111/jiec.12663

Labuschagne, C., Brent, A., & Erck, R. P. G. Van. (2007). Assessing the sustainability performances of industries . J Clean Prod Assessing the sustainability performances of industries. *Journal of Cleaner Production*, *13*, 373–385. https://doi.org/10.1016/j.jclepro.2003.10.007

Lenzo, P., Traverso, M., Salomone, R., & Ioppolo, G. (2017). Social Life Cycle Assessment in the Textile Sector: An Italian Case Study. *Sustainability*, *9*(11), 2092. https://doi.org/10.3390/su9112092

Leythienne, D., & Ronkowski, P. (2018). *A decomposition of the unadjusted gender pay gap using Structure of Earnings Survey data* (Eurostat). Luxembourg. Retrieved from https://ec.europa.eu/eurostat/de/web/products-statistical-working-papers/-/KS-TC-18-003

Li, Y., Jia, G., Cheng, Y., & Hu, Y. (2017a). Additive manufacturing technology in spare parts supply chain: a comparative study. *International Journal of Production Research*, *55*(5), 1–18. https://doi.org/10.1080/00207543.2016.1231433

Lúcio, J. (2017). *Social Life Cycle Assessment for Additive Manufacturing : A Review* (Master's thesis, Nova University of Lisbon). Retrieved from https://run.unl.pt/handle/10362/28732

Ma, J., Harstvedt, J. D., Dunaway, D., Bian, L., & Jaradat, R. (2018). An exploratory investigation of Additively Manufactured Product life cycle sustainability assessment. *Journal of Cleaner Production*, *192*, 55–70. https://doi.org/10.1016/j.jclepro.2018.04.249

Macombe, C., Leskinen, P., Feschet, P., & Antikainen, R. (2013). Social life cycle assessment of biodiesel production at three levels: A literature review and development needs. *Journal of Cleaner Production*, *52*, 205–216. https://doi.org/10.1016/j.jclepro.2013.03.026

Manik, Y., Leahy, J., & Halog, A. (2013). Social life cycle assessment of palm oil biodiesel: A case study in Jambi Province of Indonesia. *International Journal of Life Cycle Assessment*, *18*(7), 1386–1392. https://doi.org/10.1007/s11367-013-0581-5

Martínez-Blanco, J., Lehmann, A., Muñoz, P., Antón, A., Traverso, M., Rieradevall, J., & Finkbeiner, M. (2014). Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment. *Journal of Cleaner Production*, *69*, 34–48. https://doi.org/10.1016/j.jclepro.2014.01.044

Mathe, S. (2014). Integrating participatory approaches into social life cycle assessment: The SLCA participatory approach. *International Journal of Life Cycle Assessment*, *19*(8), 1506–1514. https://doi.org/10.1007/s11367-014-0758-6

Meredith, J. (1998). Building operations management theory through case and field research. *Journal of Operations Management*, *16*(4), 441–454. https://doi.org/10.1016/S0272-6963(98)00023-0

Montevecchi, F., Venturini, G., Scippa, A., & Campatelli, G. (2016). Finite Element Modelling of Wire-arc-additive-manufacturing Process. *Procedia CIRP, Proceedings - CIRPe 2016: The 5th CIRP Global Web Conference Research and Innovation for Future Production*, *55*, 109–114. https://doi.org/10.1016/j.procir.2016.08.024

Nagarajan, H. P. N., & Haapala, K. R. (2018). Characterizing the influence of resource-energy-exergy factors on the environmental performance of additive manufacturing systems. *Journal of Manufacturing Systems*, *48*, 87–96. https://doi.org/10.1016/j.jmsy.2018.06.005

O'Brien, M., Doig, A., & Clift, R. (1996). Social and environmental life cycle assessment (SELCA). *The International Journal of Life Cycle Assessment*, *1*(4), 231–237.

https://doi.org/10.1007/BF02978703

Paragahawewa, U., Blackett, P., & Small, B. (2009). *Social Life Cycle Analysis (S-LCA): Some Methodological Issues and Potential Application to Cheese Production in New Zealand. AgResearch*. Retrieved from http://www.saiplatform.org/uploads/Library/SocialLCA-FinalReport_July2009.pdf

Peng, T., Kellens, K., Tang, R., Chen, C., & Chen, G. (2018). Sustainability of additive manufacturing: An overview on its energy demand and environmental impact. *Additive Manufacturing*, *21*, 694–704. https://doi.org/10.1016/j.addma.2018.04.022

Petti, L., Serreli, M., & Di Cesare, S. (2016). Systematic literature review in social life cycle assessment. *The International Journal of Life Cycle Assessment*, 422–431. https://doi.org/10.1007/s11367-016-1135-4

Prasara-A, J., & Gheewala, S. H. (2018). Applying Social Life Cycle Assessment in the Thai Sugar Industry: Challenges from the field. *Journal of Cleaner Production*, *172*, 335–346. https://doi.org/10.1016/j.jclepro.2017.10.120

Reitinger, C., Dumke, M., Barosevcic, M., & Hillerbrand, R. (2011). A conceptual framework for impact assessment within SLCA. *International Journal of Life Cycle Assessment*, *16*(4), 380–388. https://doi.org/10.1007/s11367-011-0265-y

Rev, J., Couture, J., & Parent, J. (2015). *Socioeconomic LCA of Milk Production in Canada*. https://doi.org/10.1007/978-981-287-296-8

Ribeiro, A. (2017). *Additive manufacturing social impacts : a conceptual mode*l (Master's thesis, Nova University of Lisbon).

Schoeneboom, J., Saling, P., & Gipmans, M. (2012). AgBalance Technical background paper, 1–38.

Siebert, A., Bezama, A., O'Keeffe, S., & Thrän, D. (2018). Social life cycle assessment indices and indicators to monitor the social implications of wood-based products. *Journal of Cleaner Production*, *172*, 4074–4084. https://doi.org/10.1016/j.jclepro.2017.02.146

Singh, R. K., & Gupta, U. (2017). Social life cycle assessment in Indian steel sector: a case study. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-017-1427-3

Stuart, I., Mccutcheon, D., Handfield, R., Mclachlin, R., & Samson, D. (2002). Effective case research in operations management : a process perspective. *Journal of Operations Management*, *20*, 419–433. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0272696302000220

Sureau, S., Mazijn, B., Garrido, S. R., & Achten, W. M. J. (2017). Social life-cycle assessment frameworks: a review of criteria and indicators proposed to assess social and socioeconomic impacts. *International Journal of Life Cycle Assessment*, 1–17. https://doi.org/10.1007/s11367-017-1336-5

The Interorganizational Committee on Guidelines and Principles for Social Impact Assessment. (1994). Guidelines and principles for social impact assessment. *Environmental Impact Assessment Review*, *15*(1). https://doi.org/10.1016/0195-9255(94)00026-W

Traverso, M., Asdrubali, F., Francia, A., & Finkbeiner, M. (2012). Towards life cycle sustainability assessment: An implementation to photovoltaic modules. *International Journal of Life Cycle Assessment*, *17*(8), 1068–1079. https://doi.org/10.1007/s11367-012-0433-8

Traverso, M., Bell, L., Saling, P., & Fontes, J. (2016). Towards social life cycle assessment: a quantitative product social impact assessment. *The International Journal of Life Cycle Assessment*, 597–606. https://doi.org/10.1007/s11367-016-1168-8

Tsalis, T., Avramidou, A., & Nikolaou, I. E. (2017). A social LCA framework to assess the corporate social profile of companies: Insights from a case study. *Journal of Cleaner Production*, *164*, 1665–

1676. https://doi.org/10.1016/j.jclepro.2017.07.003

Udo de Haes, H. A., Jolliet, O., Norris, G., & Saur, K. (2002). UNEP/SETAC Life Cycle Initiative: Background, aims and scope. *International Journal of Life Cycle Assessment*, *7*(4), 192–195. https://doi.org/10.1007/BF02978872

UNEP/SETAC. (2009). *Guidelines for Social Life Cycle Assessment of Products* (Vol. 15). https://doi.org/DTI/1164/PA

UNEP/SETAC. (2013). The Methodological Sheets for Sub-Categories in Social Life Cycle assessment in S Ocial L Ife C Ycle a Ssessment (S-LCA).

van Haaster, B., Ciroth, A., Fontes, J., Wood, R., & Ramirez, A. (2017). Development of a methodological framework for social life-cycle assessment of novel technologies. *International Journal of Life Cycle Assessment*, *22*(3), 423–440. https://doi.org/10.1007/s11367-016-1162-1

Voss, C., Tsikriktsis, N., & Frohlich, M. (2002). Case research in operations management, *22*(2), 195–219. https://doi.org/10.1108/01443570210414329

Wang, S.-W., Hsu, C.-W., & Hu, A. H. (2016). An analytic framework for social life cycle impact assessment—part 1: methodology. *The International Journal of Life Cycle Assessment*, *21*(10), 1514–1528. https://doi.org/10.1007/s11367-016-1114-9

Wang, S. W., Hsu, C. W., & Hu, A. H. (2017). An analytical framework for social life cycle impact assessment—part 2: case study of labor impacts in an IC packaging company. *International Journal of Life Cycle Assessment*, *22*(5), 784–797. https://doi.org/10.1007/s11367-016-1185-7

Wangel, A. (2014). SLCA scenarios: engaging producers and consumers in new domestic oyster value chains in Denmark. *4th International Seminar in Social LCA*, 152–156. Retrieved from internal-pdf://0356426808/Wangel-SLCA scenarios_ engaging producers and.pdf

Wu, B., Pan, Z., Ding, D., Cuiuri, D., Li, H., Xu, J., & Norrish, J. (2018). A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement. *Journal of Manufacturing Processes*, *35*, 127–139. https://doi.org/10.1016/j.jmapro.2018.08.001

Wu, R., Yang, D., & Chen, J. (2014). Social Life Cycle Assessment Revisited. *Sustainability*, *6*(7), 4200–4226. https://doi.org/10.3390/su6074200

Zhou, F., Huang, S., & Liu, C. (2015). Proceedings of The Fifteenth International Conference on Electronic Business. *Proceedings of the International Conference on Electronic Business (ICEB)*, *2015–Janua*, 129–139.

Annexes

Annex A: Group 1 indicators – Application example

In this annex, the calculation method for the indicator "Non-fatal occupational accidents incidence rate" is presented. For calculation purposes, whenever it is necessary to use data collected in the organization, random data is considered.

Indicator: Non-fatal occupational accidents incidence rate

This indicator reveals the ratio of occupational injuries amongst the workforce in the company, per year per 100000 employees. This indicator is calculated through the equation demonstrated below:

$$\text{Incidence rate}(\%_{\ 000}) = \frac{Number\ of\ non\ fatal\ occupational\ accidents}{Number\ of\ workers} \times 100000\ workers$$

The first step is to collect relevant data in the organization under assessment regarding the number of non-fatal accidents occurred in the year n-1 and the total number of workers in the organization. Admitting that the number of non-fatal accidents occurred in the year n-1 is 3, and the total number of workers in the organization is 80, then the incident rate in the organization is

$$\text{Incidence rate}(\%_{\ 000}) = \frac{3}{80} \times 100000\ workers = 3750$$

Then, national statistical data is needed to calculate the social impact percentage. Admitting that the organization operates in Portugal, then the data used as PRP, must be referred to the social context in Portugal. According to the International Labour organization (ILO) database the incidence rate in Portugal, in 2015, was 2954,2 ($\%_{\ 000}$). The proportion between the incidence rate in the organization and the incident rate in Portugal is given by the social impact percentage calculated below.

$$Social\ impact\ \% = \frac{\text{Incidence rate in the organization}}{\text{Incidence rate in Portugal}} \times 100 = \frac{3750}{2954{,}2} \times 100 = 126{,}9\%$$

This indicator has a negative desire direction for sustainability (Table 3.2). The social impact percentage calculated must be classified into one of the nine categories of social impacts percentages of the scoring systems presented in Table 3.5. As can be observed, the social impact percentage calculated (126.9%) falls within the range of 125% to 150%, therefore the final score assigning to the indicator is 2. Table A.1 summarizes the calculation method used in this example.

Table A.1 - An illustrative example for score calculation of indicator in Group 1

Indicator	**Incidence rate in the organization (% 000) (a)**	**Incidence rate in Portugal (% 000) (b)**	**Social impact percentage (=((a)/(b)) ×100) (%)**	**Desired direction for sustainability**	**Score**
Non-fatal occupational accidents incidence rate	3750	2954,2 [a]	126,9%	Negative	2

Source: [a] https://www.ilo.org/global/statistics-and-databases/lang--en/index.htm

Annex B: Group 2 indicators – Application example

In this annex, the calculation method for the indicator " Percentage of the workforce hired locally" is presented. For calculation purposes, whenever it is necessary to use data collected in the organization, random data is considered.

<u>Indicator:</u> Percentage of the workforce hired locally

This indicator demonstrates the ratio of the workforce in the organization that are from the local community (UNEP/SETAC, 2013). The indicator is given in the form of a percentage, and its calculated through the equation presented below:

$$\text{\% of the workforce hired locally} = \frac{\text{Number of workers from the local community}}{\text{Total number of workers}} \times 100$$

In order to calculate this indicator, data must be first collected through documentation provided by the organization, regarding the actual place of residence of the workers. Assuming that the number of workers that are from the local community is 55, and the total number of workers in the organization is 100, the percentage of the workforce hired locally is:

$$\text{\% of the workforce hired locally} = \frac{55}{100} \times 100 = 55\%$$

The indicator has a positive desired for sustainability (higher the better). The percentage must be classified into one of the five categories of percentages of the scoring system presented in Table 3.6. As can be observed, the percentage calculated (55%) falls within the range of 40 - 60%, therefore the final score assigning to the indicator is 3. Table B.1 summarizes the calculation method used for this example.

Table B.1 - An illustrative example for score calculation of indicators in Group 2

Indicator	**Number of workers from the local community (a)**	**Total number of workers in the organization (b)**	**Percentage of the workforce hired locally (=((a)/(b)) ×100)**	**Desired direction for sustainability**	**Score**
Percentage of the workforce hired locally	55	100	55%	Positive	3

Annex C: Group 3 indicators – Application example

In this annex, the calculation method for the indicator " Preventive measures and emergency protocols regarding accidents & injuries " is presented. For calculation purposes, whenever it is necessary to use data collected in the organization, random data is considered.

Indicator: Preventive measures and emergency protocols regarding accidents & injuries

This indicator reveals the competence of the measures taken to ensure the well-being of the workforce (UNEP/SETAC, 2013; Ribeiro, 2017).

The first step is to collect data regarding the efforts of the organization in ensuring the health and safety of his workforce. This data can be collected through documentation provided by the organization and interviews with the managers of the organization. To have concrete proves that the measures are being executed in the organization's daily work, observations during field visits at the organization facilities should also be used to collect the necessary data.

Following the data analysis, the authors assign a level of implementation (not implemented, partially implemented or fully implemented) to each element addressed in this method, according to their interpretation of the data collected in the previous step. As shown in the example of Table C.1, if the authors considered that the elements Communication and monitoring are fully implemented (meriting a score of 1), but the elements policy, deployment and response are only partially implemented (meriting a score of 0.6), then the final score for the indicator would be 3.8 (0.6+1+0.6+1.0+0.6).

Table C.1 - An illustrative example for score calculation of indicator in Group 3

Indicator	**Element**	**Level of Implementation**	**Score**
Preventive measures and emergency protocols regarding accidents & injuries	Policy	P	0.6
	Communication	F	1
	Deployment	P	0,6
	Monitoring	F	1
	Response	P	0,6
Total Score			3,8

Notes: F = Fully Implemented, P = Partially Implemented, N = Not Implemented

Annex D: Group 4 indicators – Application example

In this annex, the calculation method for the indicator " Use of Personal Protective Equipment (PPE) " is presented. For calculation purposes, whenever it is necessary to use data collected in the organization, random data is considered.

Indicator: Use of Personal Protective Equipment (PPE)

This reveals the level of use of the personal protective equipment (PPE) by the workers, at the workplaces and situations in which their use is mandatory. It can demonstrate not only the lack of training given to workers regarding their use but also the organization's lack of control and awareness for the importance of the use of PPE's.

Since the workers of the organization are the only stakeholders affected by this indicator, the questionnaire carried out to assess the indicator, must be addressed to the workers.

The workers must respond on the basis of their perception to the question " Do you use the Personal Protective Equipment in every required workplaces and situations?", according to the five-point response scale demonstrated in Table D.1.

Table D.1 - Five-point response scale used in the example

Score	Response
1	I never use the PPE when required.
2	I rarely use the PPE when required
3	I often use the PPE when required.
4	Most of the times, I use the PPE when required.
5	I always use the PPE when required.

Assuming that the organization has 100 workers, and the results of the questionnaire are those shown below:

5 – 50 workers

4 – 20 workers

3 – 10 workers

2 – 15 workers

1 – 5 workers

The weighted average can be calculated as follows:

$$\bar{X} = \frac{5\times50+4\times20+3\times10+2\times15+1\times5}{100} = 3{,}95$$

The final score of the indicator corresponds to the exact value of the weighted average calculated, what gives a final score of 3,95. Table A.5 sums up the calculation method used for the example provided above.

Table A.5 - An illustrative example for score calculation of indicators in Group 4

Indicator	**Five-point response scale**	**Results of the questionnaire**	**Weighted Average ($\bar{X}$)**	**Score**
Do you use the Personal Protective Equipment in every required workplaces and situations?	1: I never use the PPE when required. 2: I rarely use the PPE when required 3: I often use the PPE when required. 4: Most of the times, i use the PPE when required. 5: I always use the PPE when required.	5 – 50 workers 4 – 20 workers 3 – 10 workers 2 – 15 workers 1 – 5 workers	$\bar{X} = \frac{5\times50+4\times20+3\times10+2\times15+1\times5}{100}$ $=3{,}95$	3,95

Annex E: Computational application model of the proposed SLCA methodology

This annex provides an overview of the excel file on which the computational application model of the proposed SLCA methodology was developed. The values and results presented in this annex were obtained through random data used by the author of this dissertation.

E.1. Data collection process - Manufacturing

In this annex, is presented a print shot of the excel sheet *"Data collection_Manufacturing, in which* it is possible to visualize the data required to measure 11 of the 14 indicators for the stakeholder Worker, in the life cycle stage Manufacturing.

Data Collection

Life cycle stage:	Manufacturing
Data collected from the organization:	
Reference period:	2017

Stakeholder	Nº	Indicators	Questions/Data required to measure the indicator	Data units	Data collected
Worker	1	Non-Fatal occupational accidents incidence rate	Number of non-fatal occupational accidents in the organization	Nr.	0
			Total number of workers in the organization	Nr.	50
	2	Fatal occupational accidents incidence rate	Number of fatal occupational accidents	Nr.	0
			Total number of workers in the organization	Nr.	50
	3	Use of Personal Protective Equipment (PPE) Question: "Do you use the PPE in every required workplaces and situations?"	Number of respondents anwering 5:	Nr.	10
			Number of respondents anwering 4:	Nr.	6
			Number of respondents anwering 3:	Nr.	20
			Number of respondents anwering 2:	Nr.	16
			Number of respondents anwering 1:	Nr.	10
	4	Preventive measures and emergency protocols regarding accidents and injuries	Establishment of practices or policies that address and support the integration of the measure in the organization	Descriptive	Partially implemented
			Communication of commitment for the compliance with the measure to employees, managers and other relevant stakeholders across the value chain	Descriptive	Partially implemented
			The measure has been implemented in every required situation	Descriptive	Not implemented
			Performance of continous control to ensure that managers and employees comply with the established measure	Descriptive	Partially implemented
			A review mechanism for handling complaints and suggestions has been established to ensure response	Descriptive	Partially implemented
	5	Presence of female employees in management positions	Number of female employees in management postions	Nr.	15,00
			Total number of employees in management positions	Nr.	40
	6	Gender pay gap	Average gross hourly earnings of female paid employees (=(a)/(b))	euros/hour	8,33
			Sum of the hourly wages of each female worker (a)	hours	50,00
			Number of female workers (b)	Nr.	6,00
			Average gross hourly earnings of male paid employees (=(c)/(d))	euros/hour	8,00
			Sum of the hourly wages of each male worker (c)	hours	64,00
			Number of male workers (d)	Nr.	8,00
	7	Average monthly basic remuneration of employees	Sum of the basic monthly salaries (gross amount, before the deduction of taxes and social security contributions) of each employee (all qualification levels) paid in 2017	euros	42000
			Total number of employees (all qualifications level)	Nr.	50
	8	Percentage of employees receiving minimum wages	Number of employeees receiving the minimum wage	Nr.	20
			Total number of employees in the organization	Nr.	50
	9	Employee work satisfaction Question: "Do you feel satisfied with your job?"	Number of respondents anwering 5:	Nr.	20
			Number of respondents anwering 4:	Nr.	30
			Number of respondents anwering 3:	Nr.	20
			Number of respondents anwering 2:	Nr.	15
			Number of respondents anwering 1:	Nr.	15
	10	Average weekly hours of work by full-time employee	Sum of the hours actually worked (including overtime) by each full-time employee during the reference period (year x)	hours	85000
			Total number of full-time employees in the organization	Nr.	40
	11	Presence of Child Labour	Number of children (under 15 years old) working in the organization	Nr.	1
			Total number of full-time employees in the organization	Nr.	40

Question: "Do you use the PPE in every required workplaces and situations?"
Response scale:
5 - I always use the PPE when is required.
4 - Most of the times, i use the PPE when is required.
3 - I often use the PPE when is required.
2 - I rarely use the PPE when is required.
1 - I never use the PPE when

For each of the five questions related to indicator **4** the respondent must answer:

- Not implemented,
- Partilly implemented
- Fully implemented

According to the degree of implementation verified in the organization.

Question: "Do you feel satisfied with your job?"
Response scale:
5 - Very Satisfied
4 - Moderately Satified
3 - Neutral
2 - Moderately dissatisfied
1 - Very dissatisfied

E.2. Calculation of the indicators Scores - Manufacturing

In this annex, a print shot of the excel sheet *"Indicators score_Manufacturing"* is presented. It shows all the calculation steps required to obtain the scores of 4 of the 26 indicators in the Manufacturing stage.

Calculation of the Indicators Scores

Life cycle stage:	Manufacturing
Data collected from:	

Indicator	Indicator description	Stakeholder Category	Subcategorie	Type	Indicator Group	Desired direction	Caculation method	Number of non-fatal occupational accidents	Number of workers in the reference period	Non-Fatal accidents incidence rate (a)	PRP at setor/country level (b)	Social Impact % (=(a)/(b))	Scoring system	Indicator SCORE
Fatal occupational accidents incidence rate	Reveals the number of fatal occupational accidents amongst the organization's workforce, per year per 100000 employees	Worker	Health and Safety	Quantitative	Group 1	Negative	$\text{Fatal occupational accidents incidence rate} = \frac{\text{Number of fatal occupational accidents}}{\text{Number of employees in the reference period}} \times 100000 \text{ workers}$	0	50	0	45	0,00%	Proportion / Score: >175% 1; 150 - 175% 1,5; 125 - 150% 2; 100 - 125% 2,5; 100% 3; 75 - 100% 3,5; 50 – 75% 4; 21 – 50% 4,5; <25% 5	5

Indicator	Indicator description	Stakeholder Category	Subcategorie	Type	Indicator Group	Desired direction	Caculation method	Number of workers that are from the local community	Total number of workers in the organization	% workforce hired locally	Scoring system	Indicator SCORE
Percentage of the workforce hired locally	It shows the ratio of the workforce that are from the local community	Local Community	Local Employment	Quantitative	Group 2	Positive	$\text{\% of the workforce hired locally} = \frac{\text{Number of workers from the local community}}{\text{Total number of workers in the organization}} \times 100$	15	50	30,00%	Percentage / Score: <20% 1; 20 - 40% 2; 40 - 60% 3; 60 - 80% 4; 80 - 100% 5	2

Indicator	Indicator description	Stakeholder Category	Subcategorie	Type	Indicator Group	Desired direction	Elements	Description	Degree	Score	Indicator SCORE
Organization's efforts in promoting AM education initiatives in the local community	This indicator measures the efforts of the organization in promoting the AM technology within the local community, through education initiatives	Local Community	Acess to immaterial resources	Semi-quantitative	Group 3	Positive	Policy	Establishment of practices or policies that address and support the integration of the measure in the organization	Not Implemented	0,2	3,0
							Communication	Communication of commitment for the compliance with the measure to employees, managers and other relevant stakeholders across his value chain	Not Implemented	0,2	
							Deployment	The measure has been implemented in every required situation	Partially implemented	0,6	
							Monitoring	Performance of continuous control to ensure that managers and employees comply with the established measure	Fully implemented	1,0	
							Response	A review mechanism for handling complaints and suggestions has been established to ensure response	Fully implemented	1,0	

Indicator	Indicator description	Stakeholder Category	Subcategorie	Type	Indicator Group	Desired direction	Caculation method	Question	Five-point Scale Response Scale	Number of people answering 5	Number of people answering 4	Number of people answering 3	Number of people answering 2	Number of people answering 1	Indicator SCORE
Employee work satisfaction	It reveals the level of satisfaction of the employees regarding their job and also their willingness to continue working in the same organization	Worker	Psychological working conditions	Semi-quantitative	Group 4	Positive	Five-point Scale Response Survey	Do you feel satisfied with your job?	5 - Very Satisfied 4 - Moderately Satified 3 - Neutral 2 - Moderately dissatisfied 1 - Very dissatisfied	15	30	5	20	4	3,4

E.3. Calculation of the Life Cycle stage Score - Manufacturing

In this annex, a print shot of the excel sheet " Manufacturing_SCORE" is presented. It shows how the indicators scores are aggregated into a single score, between 0,2 and 1, that correspond to the life cycle stage SCORE, in this case, the Manufacturing stage score.

Calculation of the Life Cycle Stage SCORE

Life cycle stage:	**Manufacturing**
Final score (0,2 - 1):	**0,70**
Social impact:	**Positive Social Impact**

Stakeholder Category	Subcategory	Indicator	Indicator score	Number of indicatotrs subcategory (a)	Number of indicators stakehoder (b)	Indicator weight (c) $\frac{1}{\sum(b)_i}$	Scoring scale (d)		Min - Max Normalized indicator score min $\frac{(c)\times(d=1)}{5}$	max $\frac{(c)\times(d=5)}{5}$	Normalized indicator score (e)	Min-Max Subcategory aggegated score		Subcategory aggregated score (f) $\sum^{(a)}(e)_i$	Min-Max Stakeholder category aggegated score		Stakeholder category (g) aggregated score $\sum^{(b)}(f)_i$	Min-Max Life Cycle stage aggegated score		Life cycle stage score (h) $\sum(g)_i$
Worker	Health and safety	Non-Fatal occupational accidents incidence rate	5,0	4	14	0,03846	1	5	0,0077	0,0385	0,0385	0,0308	0,1538	0,1188	0,1077	0,5385	0,3668	0,2	1,0	0,70
		Fatal occupational accidents incidence rate	5,0			0,03846	1	5	0,0077	0,0385	0,0385									
		Use of Personal Protective Equipment (PPE)	2,8			0,03846	1	5	0,0077	0,0385	0,0218									
		Preventive measures and emergency protocols regarding accidents and injuries	2,6			0,03846	1	5	0,0077	0,0385	0,0200									
	Equal opportunities	Presence of female employees in management positions	5,0	2		0,03846	1	5	0,0077	0,0385	0,0385	0,0154	0,0769	0,0769						
		Gender pay gap	5,0			0,03846	1	5	0,0077	0,0385	0,0385									
	Fair salary	Average monthly basic remuneration of employees	2,5	2		0,03846	1	5	0,0077	0,0385	0,0192	0,0154	0,0769	0,0269						
		Percentage of employees receiving minimum wages	1,0			0,03846	1	5	0,0077	0,0385	0,0077									
	Psychological working conditions	Employee work satisfaction	3,3	1		0,03846	1	5	0,0077	0,0385	0,0250	0,0077	0,0385	0,0250						
	Working hours	Average weekly hours of work by full-time employee	3,5	1		0,03846	1	5	0,0077	0,0385	0,0269	0,0077	0,0385	0,0269						
	Child labour	Presence of child labour in the organization	5,0	1		0,03846	1	5	0,0077	0,0385	0,0385	0,0077	0,0385	0,0385						
	Social benefit /Social security	Access to legal social benefits	3,0	3		0,03846	1	5	0,0077	0,0385	0,0231	0,0231	0,1154	0,0538						
		Percentage of workers educated by the organization regarding AM technology	2,0			0,03846	1	5	0,0077	0,0385	0,0154									
		Percentage of qualified workers in the organization	2,0			0,03846	1	5	0,0077	0,0385	0,0154									
Local Community	Local employment	Percentage of the workforce hired locally	1,0	3	4	0,03846	1	5	0,0077	0,0385	0,0077	0,0231	0,1154	0,0692	0,0308	0,1538	0,0954			
		Percentage of spending on locally-based suppliers	5,0			0,03846	1	5	0,0077	0,0385	0,0385									
		Percentage of Local suppliers	3,0			0,03846	1	5	0,0077	0,0385	0,0231									
	Access to immaterial	Organization's efforts in promoting AM education initiatives in the local community	3,4	1		0,03846	1	5	0,0077	0,0385	0,0262	0,0077	0,0385	0,0262						
Value chain actos	Promoting social responsibility	Integration of ethical, social and environmental criteria in purchasing and distribution policy	4,6	1	3	0,03846	1	5	0,0077	0,0385	0,0354	0,0077	0,0385	0,0354	0,0231	0,1154	0,0938			
	Respect of intellectual property rights	Organization's policy and practice regarding the protection of intellectual properties rights	4,6	1		0,03846	1	5	0,0077	0,0385	0,0354	0,0077	0,0385	0,0354						
	Supplier Relationships	Payments on time to suppliers	3,0	1		0,03846	1	5	0,0077	0,0385	0,0231	0,0077	0,0385	0,0231						
Society	Prevention and Mitigation of Conflicts	Organizations' efforts to prevent the manufacturing of weapons using AM	3,0	1	1	0,03846	1	5	0,0077	0,0385	0,0231	0,0077	0,0385	0,0231	0,0077	0,0385	0,0231			
Consumer	Health and safety	Organization's efforts and measures to protect consumer health and safety	3,0	2	4	0,03846	1	5	0,0077	0,0385	0,0231	0,0154	0,0769	0,0615	0,0308	0,1538	0,1200			
		Percentage of consumers negatively affected regarding their health and safety	5,0			0,03846	1	5	0,0077	0,0385	0,0385									
	Privacy	Organization's efforts and measures to ensure the protection of consumer privacy	2,6	2		0,03846	1	5	0,0077	0,0385	0,0200	0,0154	0,0769	0,0585						
		Percentage of the consumers affected by situations of breach of privacy or loss of data	5,0			0,03846	1	5	0,0077	0,0385	0,0385									
					26															
					Total															

E.4. Calculation of the AM Product Final SCORE

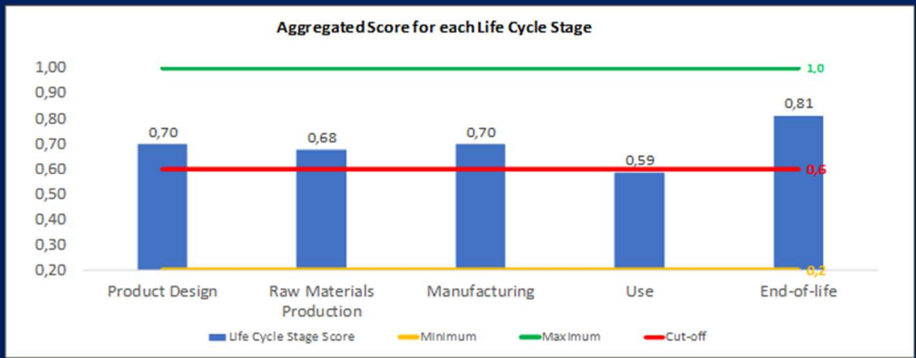
In this annex, is presented a print shot of the excel sheet *"AM Product Life Cycle_SCORE”*. It shows the scores of the five cycle stages considered in the study. The aggregation of these scores gives the overall score of the AM product life cycle, between 1 and 5, which corresponds to a specific social impact.

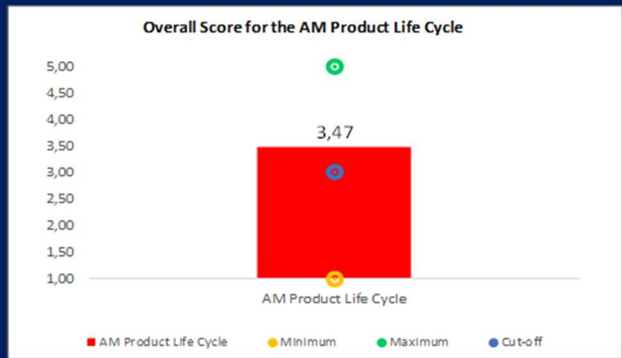
Calculation of the AM Product Final SCORE

Overall SCORE of the AM Product Life Cycle (1 - 5): 3,47

Overall SOCIAL IMPACT of the AM Product Life Cycle: Positive Social Impact

		AM Product Life Cycle														
		Product Design			Raw Materials Production			Manufacturing			Use			End-of-life		
Stakeholder Category	Subcategory	Subcategory Score	Stakeholder score	Life Cycle Stage SCORE	Subcategory Score	Stkeholder score	Life Cycle Stage SCORE	Subcategory Score	Stkeholder score	Life Cycle Stage SCORE	Subcategory Score	Stkeholder score	Life Cycle Stage SCORE	Subcategory Score	Stkeholder score	Life Cycle Stage SCORE
Worker	Health and safety	0,1283	0,3771	(0,2 - 1)	0,1218	0,3482	(0,2 - 1)	0,1188	0,3668	(0,2 - 1)	0,1039	0,3374	(0,2 - 1)	0,1414	0,4221	(0,2 - 1)
	Equal opportunities	0,0423			0,0308			0,0769			0,0654			0,0731		
	Psychological working conditions	0,0296			0,0264			0,0250			0,0219			0,0308		
	Fair salary	0,0538			0,0462			0,0269			0,0269			0,0269		
	Working hours	0,0154			0,0154			0,0269			0,0269			0,0269		
	Child labour	0,0385			0,0385			0,0385			0,0385			0,0385		
	Social benefit /Social security	0,0692			0,0692			0,0538			0,0538			0,0846		
Local Community	Local employment	0,0462	0,0662	0,70	0,0692	0,0831	0,68	0,0692	0,0954	0,70	0,0462	0,0569	0,59	0,1154	0,1262	0,81
	Access to immaterial resources	0,0200			0,0138			0,0262			0,0108			0,0108		
Value chain actors	Promoting social responsibility	0,0262	0,0846		0,0262	0,0908		0,0354	0,0938		0,0354	0,0569		0,0354	0,0815	
	Respect of intellectual property rights	0,0200			0,0262			0,0354			0,0138			0,0385		
	Supplier Relationships	0,0385			0,0385			0,0231			0,0077			0,0077		
Society	Prevention and Mitigation of Conflicts	0,0385	0,0385		0,0262	0,0262		0,0231	0,0231		0,0138	0,0138		0,0354	0,0354	
Consumer	Health and safety	0,0615	0,1323		0,0738	0,1292		0,0615	0,1200		0,0492	0,1200		0,0677	0,1446	
	Privacy	0,0708			0,0554			0,0585			0,0708			0,0769		
		Overall Score of the AM Product Life Cycle (1 - 5): 3,47														





Annex F: Questionnaire to be filled out by the respondent

In this annex, the questionnaire developed for the present study is presented.

Interview protocol

This interview protocol aims to support a research to identify the social impacts from the use of additive manufacturing (AM) technology.

I am a student of the integrated master 's degree in industrial engineering and management of FCT - UNL and intend to use the data obtained through this questionnaire in the context of my dissertation, which focuses on the topic mentioned above.

The research is developed under the project FIBR3D - Hybrid processes based on additive manufacture, at the UNIDEMI / FCT - UNL.: http://www.unidemi.com/.

The questionnaire should be answered by a manager or an industrial production engineer. It can be responded and sent later by e-mail to fm.lourenco@campus.fct.unl.pt.

Part I - Identification of Social Impacts

The questionnaire pretends to assess the effects of additive manufacturing technology in your company's social performance.
Please state how AM technology improve or decrease your company's social performance. Give your perception about it by stating for each indicator whether AM **increases**, **decreases** or **does not have any impact**. Please always try to justify your choices for each indicator.

Social theme	Nº	Indicator	The use of AM technology:				Comment / Justification
			Do not know	Decreases	No impact	Increases	
Health and safety	1	Non-Fatal occupational accidents incidence rate					
	2	Fatal occupational accidents incidence rate					
	3	Use of personal protective equipment (PPE)					
	4	Preventive measures and emergency protocols regarding accidents and injuries					
Equal opportunities/ Discrimination	5	Presence of female employees in management positions					
	6	Gender pay gap					
Fair salary	7	Average monthly basic remuneration of employees					
	8	Percentage of employees receiving minimum wages					
Working conditions	9	Employee work satisfaction					
Working hours	10	Average weekly hours of work by full-time employee					
Child labour	11	Presence of child labour in the organization					
Social benefit/Social security	12	Access to legal social benefits according to the country laws					
	13	Percentage of workers educated by the organization regarding AM technology					
	14	Percentage of qualified workers in the organization					

Social theme	N°	Indicator	The use of AM technology:				Comment / Justification
			Do not know	Decreases	No impact	Increases	
Local employment	15	Percentage of the workforce hired locally					
	16	Percentage of spending on locally-based suppliers					
	17	Percentage of local suppliers					
Access to immaterial resources	18	Organization's efforts in promoting AM education initiatives in the local community (<60km)					
Promoting social responsibility	19	Integration of ethical, social and environmental criterions in purchasing and distribution policy					
Respect of intellectual property rights	20	Organization's policy and practice regarding the protection of intellectual properties rights					
Supplier relationships	21	Payments on time to suppliers					
Prevent and mitigation of conflicts	22	Organization's efforts to prevent the manufacturing of armed conflicts weapons using AM					
Consumer's health and safety	23	Percentage of consumers negatively affected regarding their health and safety					
	24	Organization's efforts and measures to protect consumer health and safety					
Consumer's privacy	25	Percentage of the consumers affected by situations of breach of privacy or loss of data					
	26	Organization's efforts and measures to ensure the protection of consumer privacy					

Part II – Company Characterization

1 – Company data

1.1 Company Name: ____________________________________

1.2 Business volume in 2017: ____________________________________

1.3 Number of Employees:

☐ < 10 ☐ 10 to 49 ☐ 50 to 250 ☐ > 250

1.4 Please insert the number of employees with the following academic degrees.

	Academic degrees			
	12º grade	BSc (Bachelor of Science)	MSc (Master of Science)	PhD (Doctor of Philosophy)
Number of employees				

1.5 Company age:

☐ < 2 years ☐ More than 2 to 5 years ☐ More than 5 to 10 years ☐ > 10 years

2 – Characterization of the Company's Processes and Products

2.1 What type of AM technology equipment does the company have?

____

2.2 What was the year of introduction of the AM technology in the company? If it was more than 5 years ago, have investments been made (or are being planned) to upgrade the equipment/increase production capacity?

____

2.3 What are the main products produced by the AM technology?

____

2.4 What is the main sector of economic activity of your clients?

____

2.5 What are the main suppliers of your company? What is the location of each of these suppliers?

____

Confidentiality Commitment

The information obtained through this protocol, as well as any document provided by the company, constitutes anonymous information in support of this research work. It will be used to establish the current state of the art in terms of the social impacts of additive manufacturing technology.

In addition, it is intended to identify the needs and requirements of the companies and society in general, so that they can be duly considered in future work.

The articles, dissertations and published materials within this project may include the results of this preliminary study. However, this information will be treated in aggregate and global form, without custom association with the companies in question.

The collaboration of the participants will be publicly recognized, in particular by including the name of the company in the articles to be carried out, unless the company wishes to remain anonymous.

The Research Team

Francisco Lourenço

Helena Carvalho

November, 2018